NSTX

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Turbulence Characteristics Near the L-H Transition in NSTX Ohmic Discharges

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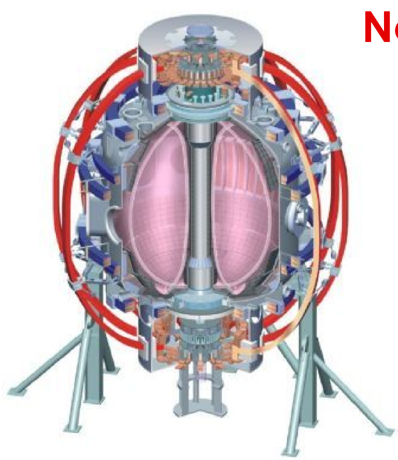

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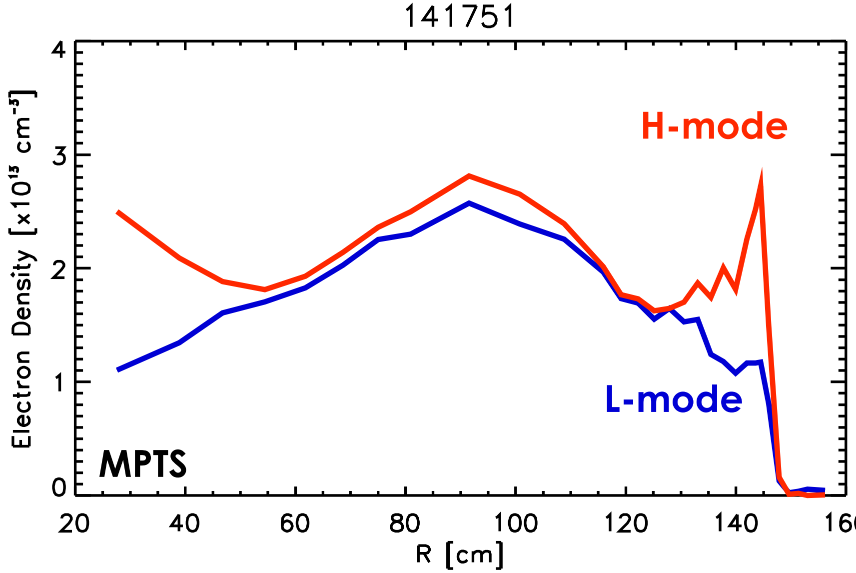
Introduction

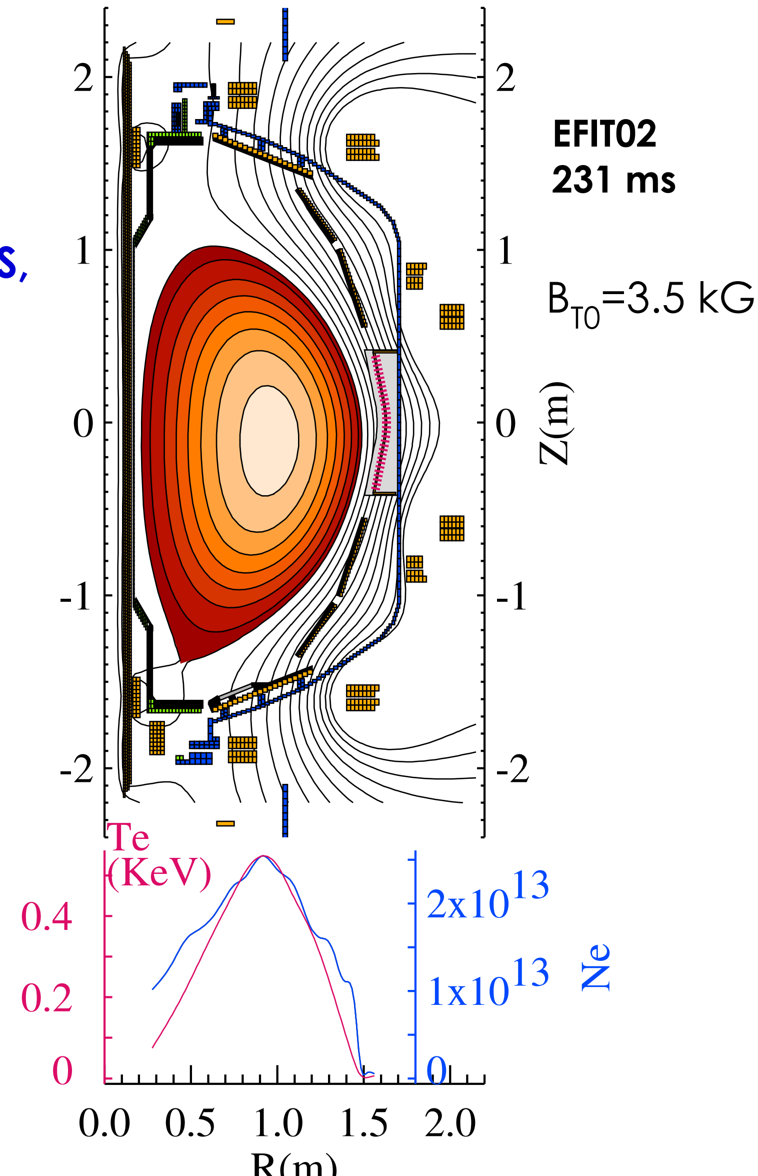
- Recent observations of interplay between turbulence and GAM-like oscillations during NSTX L-mode from gas-puff imaging (GPI).
- Trigger mechanism(s) for L-H transitions remain elusive.
- Newer diagnostics such as Doppler backscattering have shown the need to look at a broad k-range of turbulence with good resolution.
- Revisit FM reflectometry ($\Delta t \lesssim 10$ μs, $n_e = 0.2\text{-}3.5\times10^{13}$ 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 ($\lesssim 22$ cm^{-1}): $k_r(R,t)$
- Results near the Ohmic L-H transitions
  - At ETB location: steep gradient, decrease in correlation length.
  - Drop in k_r spectral power at ETB location.
  - Evidence of oscillation in k_r spectral power prior to L-H transition.

Ohmic H-Modes Targets for L-H Transition Studies

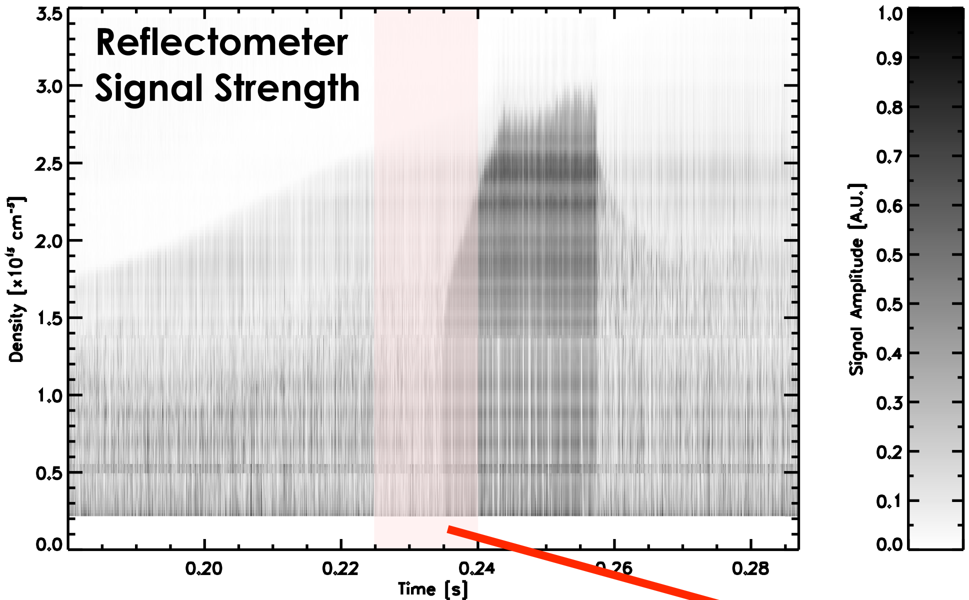
- **Benefits of Ohmic discharges:**
  - No fast particle-driven modes to mask turbulence spectrum
  - No external momentum input
  - Lack of NB-based diagnostics (CHERS, MSE, BES, etc.)
- **Discharge parameters:**

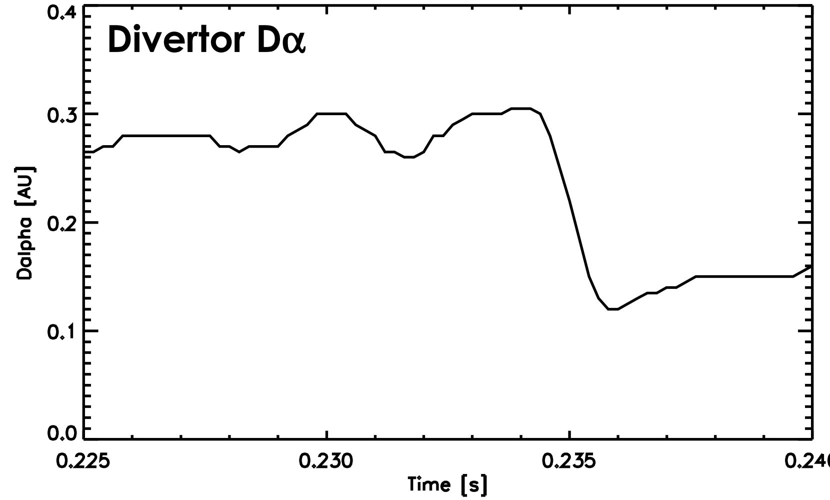
  B_T=3.5 kG, I_p=800 kA, LSN, Deut.
- **Edge density ears in H-mode limits access to core.**

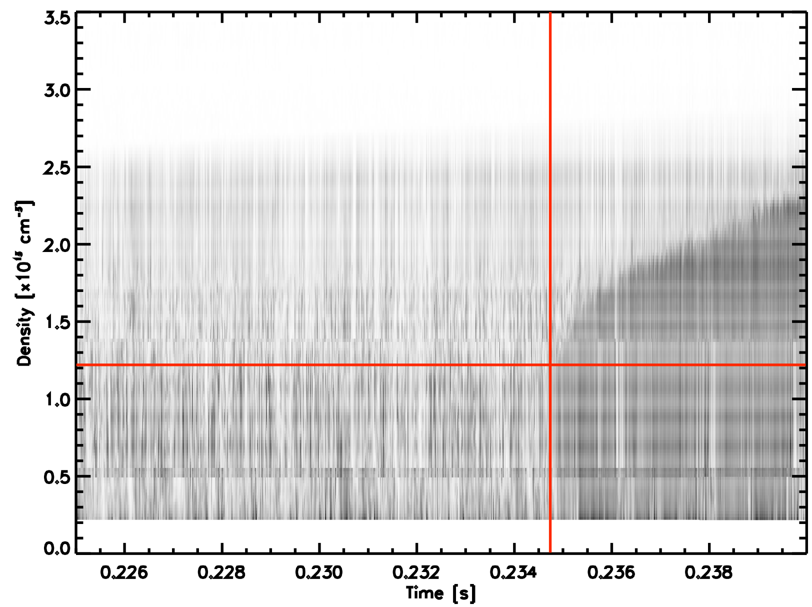




Precise L-H Transition Timing and ETB Position Identified from Signal Strength



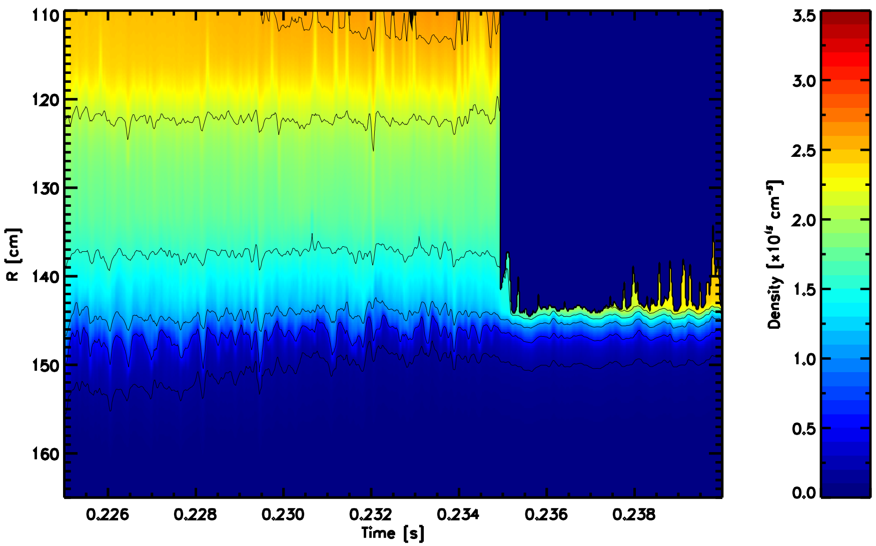




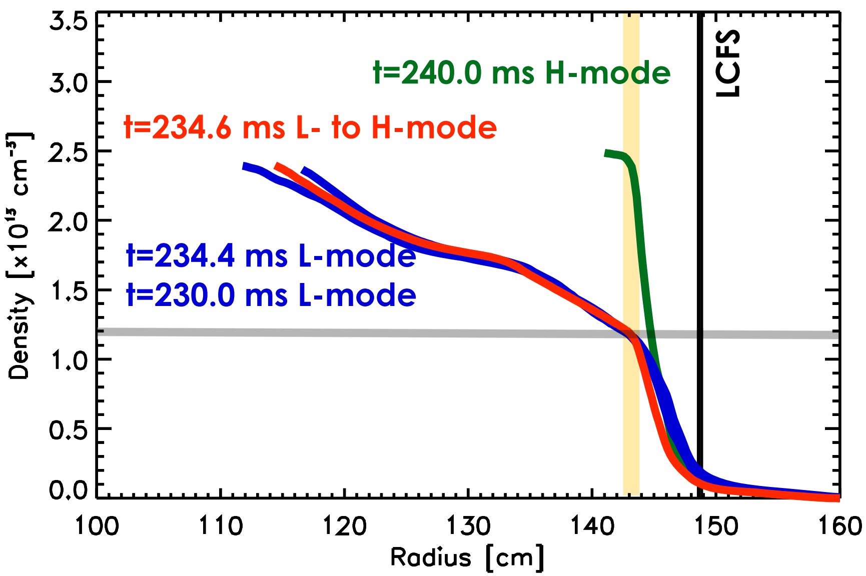
- For H-mode edge,
  - Turbulence reduction -> specular reflection -> stronger signal.
- t=234.64 ms
- n_e=1.2x10^{13} cm^{-3}

Density Gradient Steepens at ETB Location

Density Profile Contours

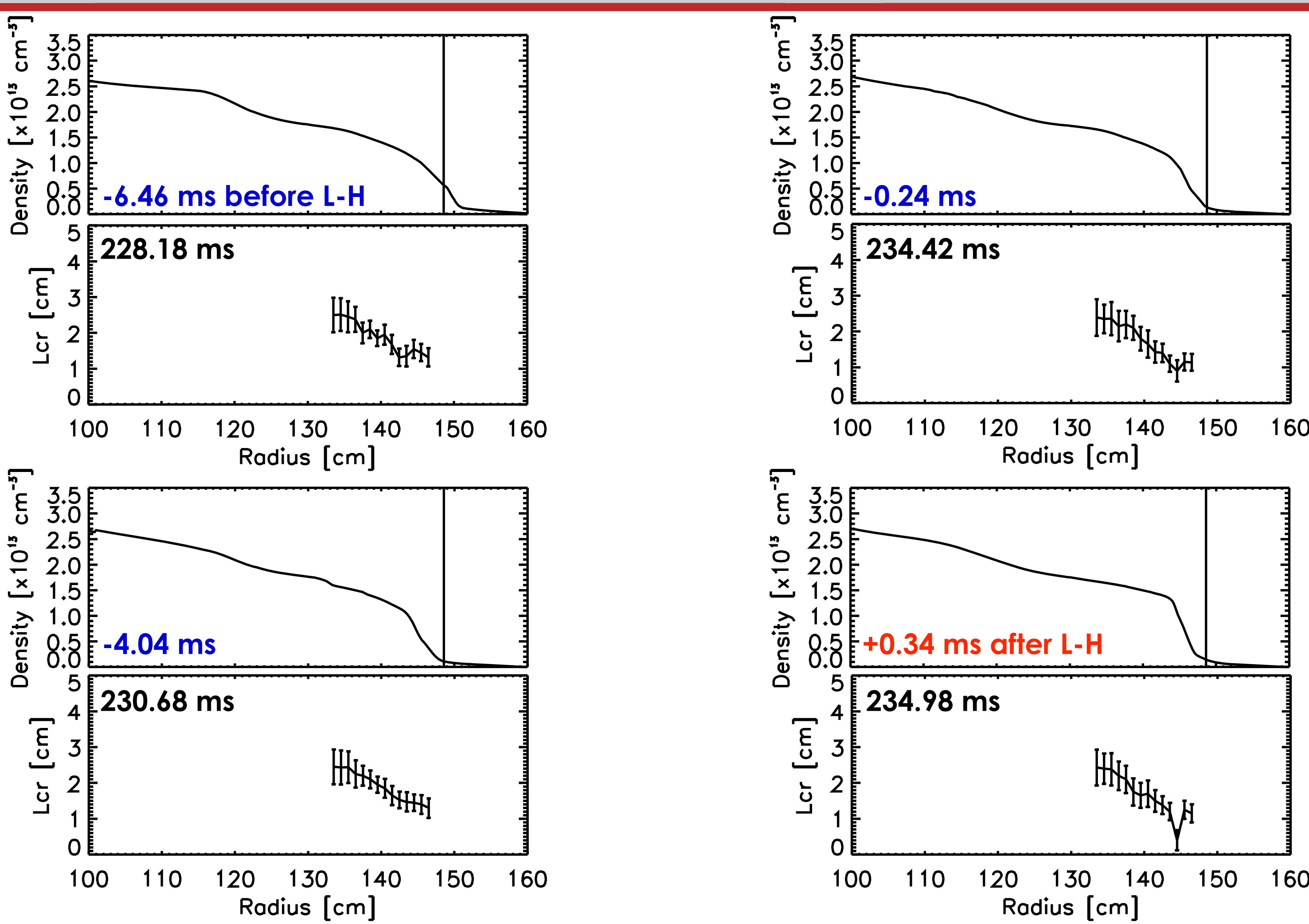


Density Profile Near L-H Transition



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

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

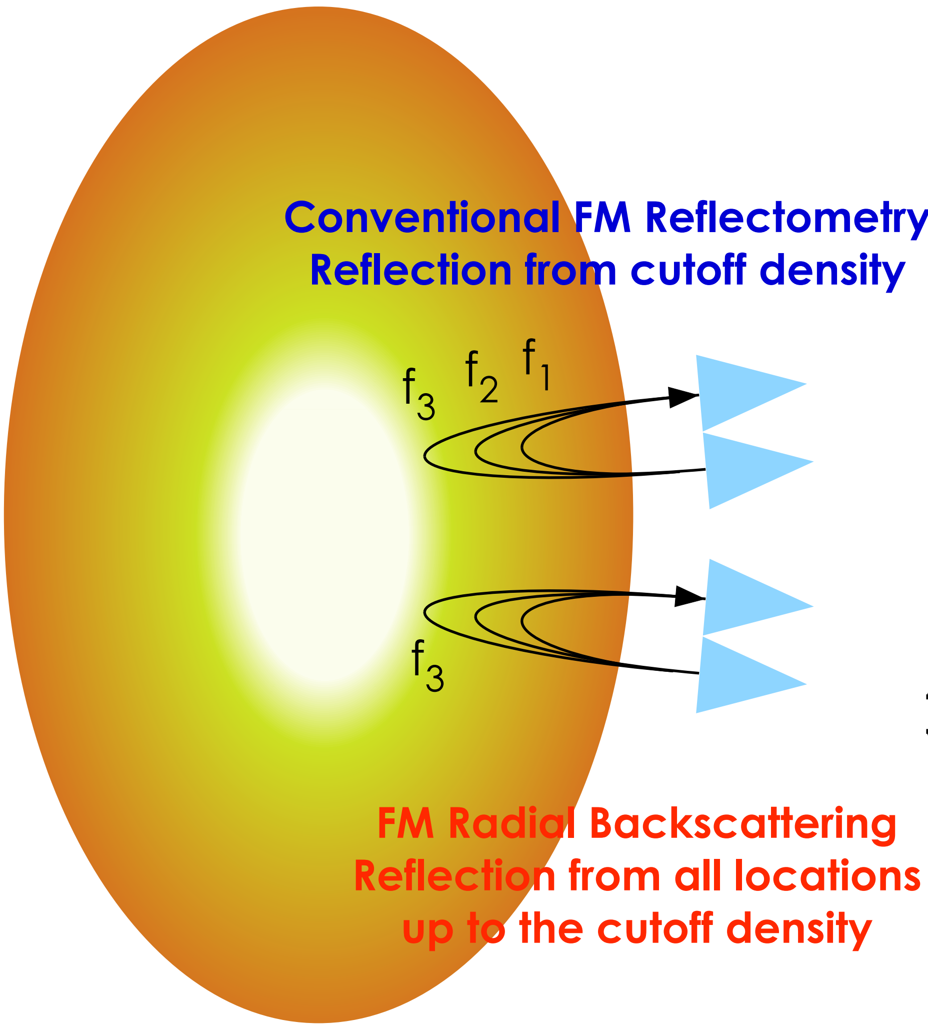


- Radial correlation length decreases prior (<1 ms) to L-H transition
  - Statistical method which requires $\Delta t \geq 0.36$ ms resolution

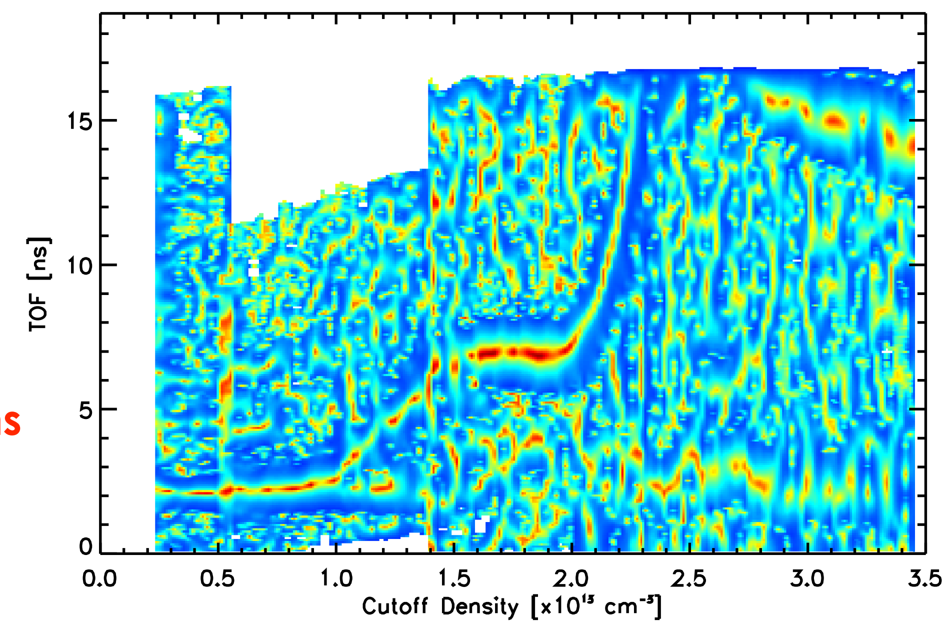
Spatially-Resolved k_r Spectrum

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

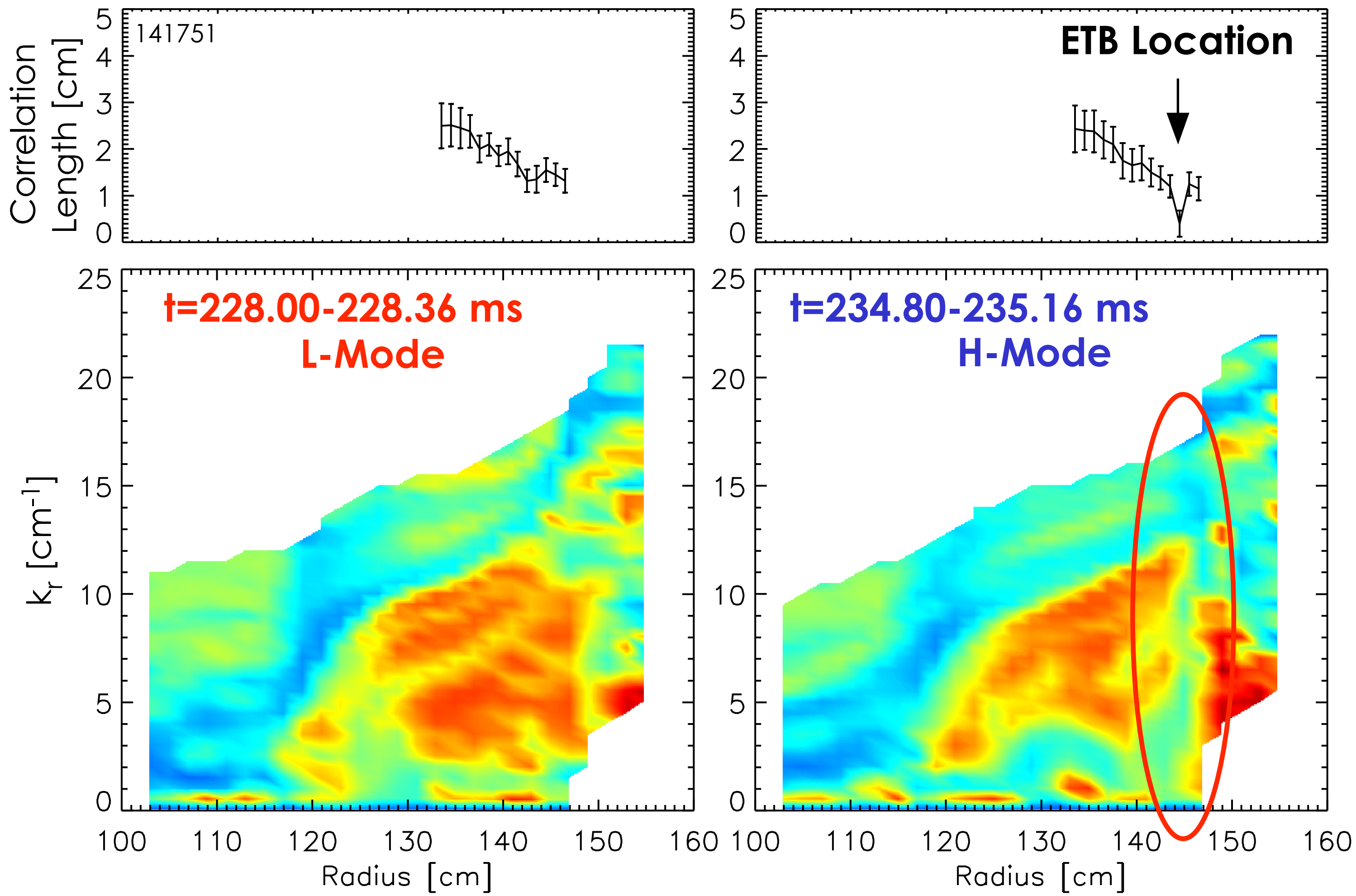
$$k_{\mathrm{s}}(r, f) = 2\,k(r, f)$$



Reflectometry/Backscattering Radar Image

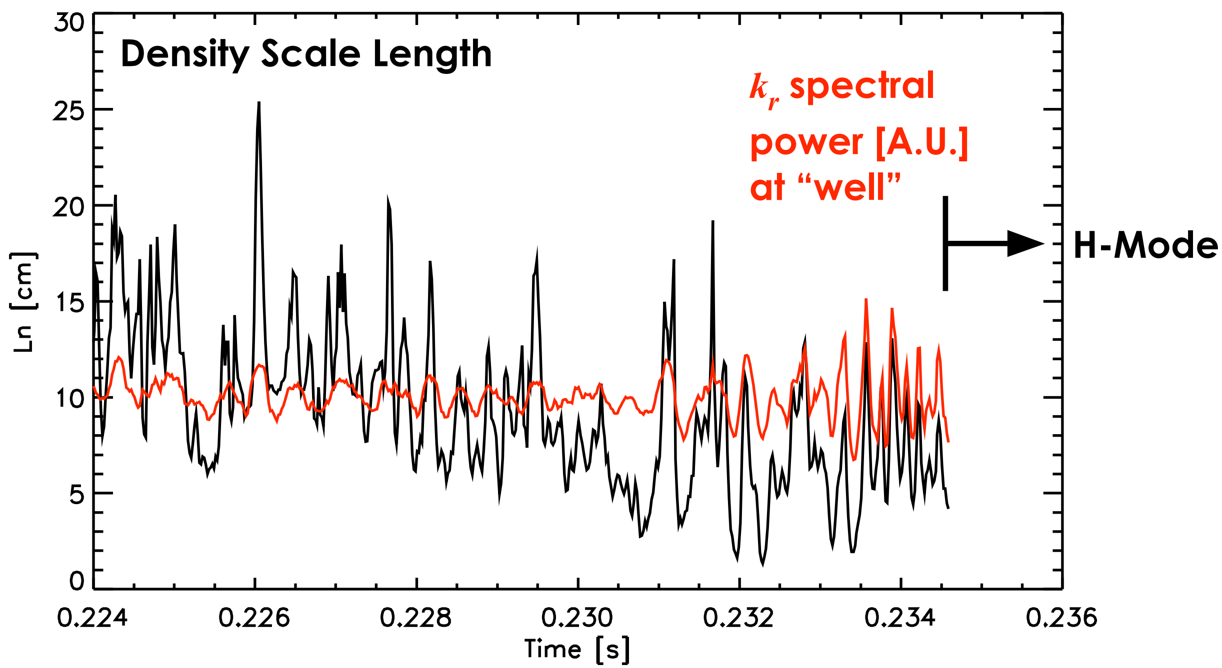


k_r Spectrum: "Well" Develops at ETB Location



Oscillations During L-Mode Phase

- **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.



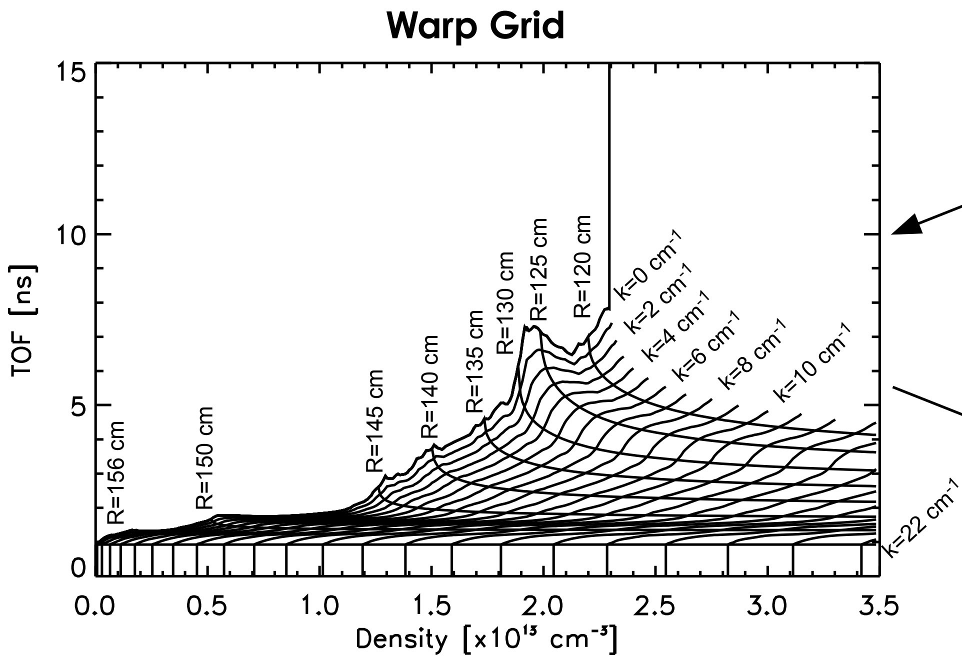
  - Could be sign of underlying flow/turbulence dynamics.

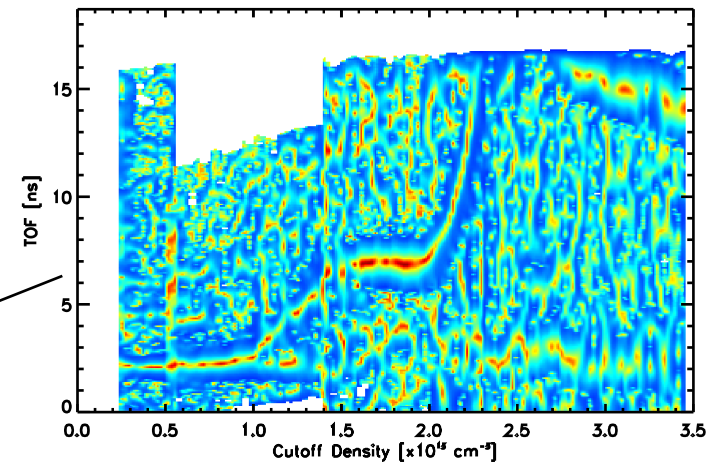
Summary and Future Work

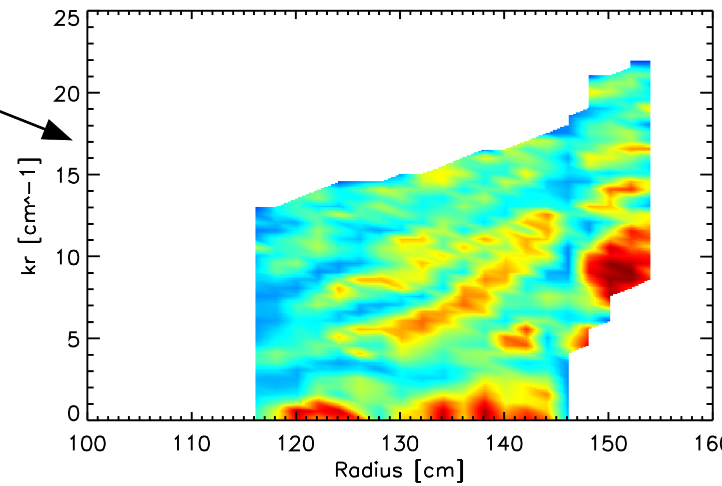
- Ohmic H-modes were characterized using new millimeter-wave hardware and diagnostic techniques.
- Localized (to ETB) changes in turbulence at the L-H transition:
  - Drop in $\delta n/n$
  - Reduction in radial correlation length
  - Steepening of the density gradient
  - k_r-spectrum spatial "well" 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
    - Doppler reflectometry proposed for NSTX-U
- Future directions:
  - Mid-radius and core L-mode (and H-mode) studies, ITB's
  - Detailed comparisons with GPI and BES
  - Absolute k_r-spectrum levels and shapes using synthetic diagnostics (multi-dimensional full-wave codes)

Transformation Equivalent to Image Warping

- **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.

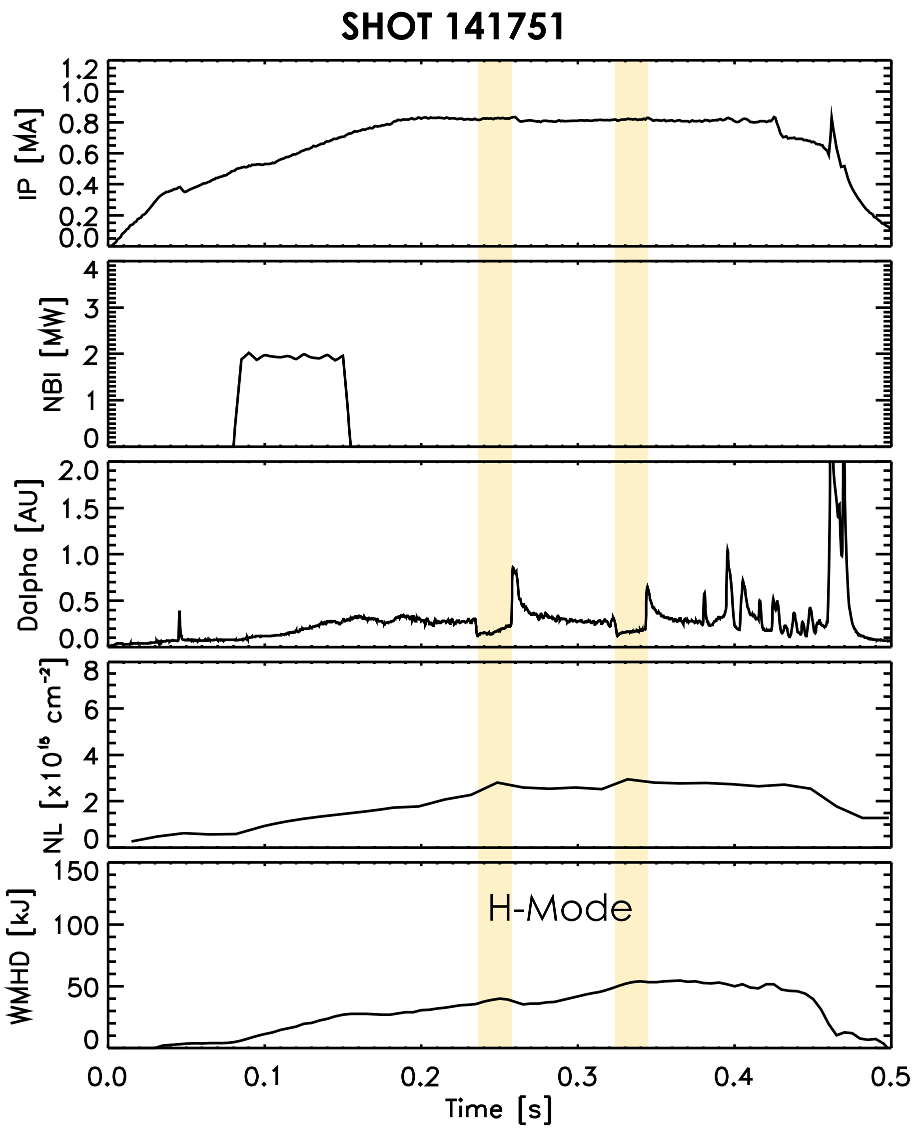


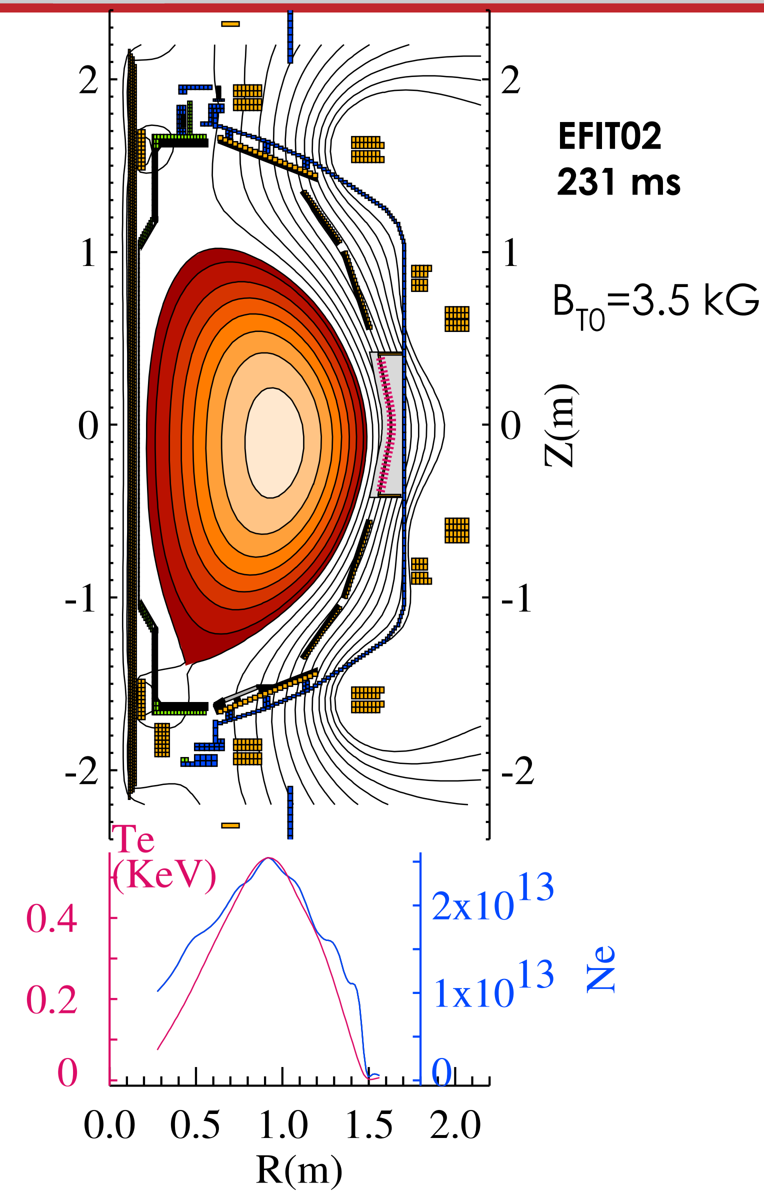




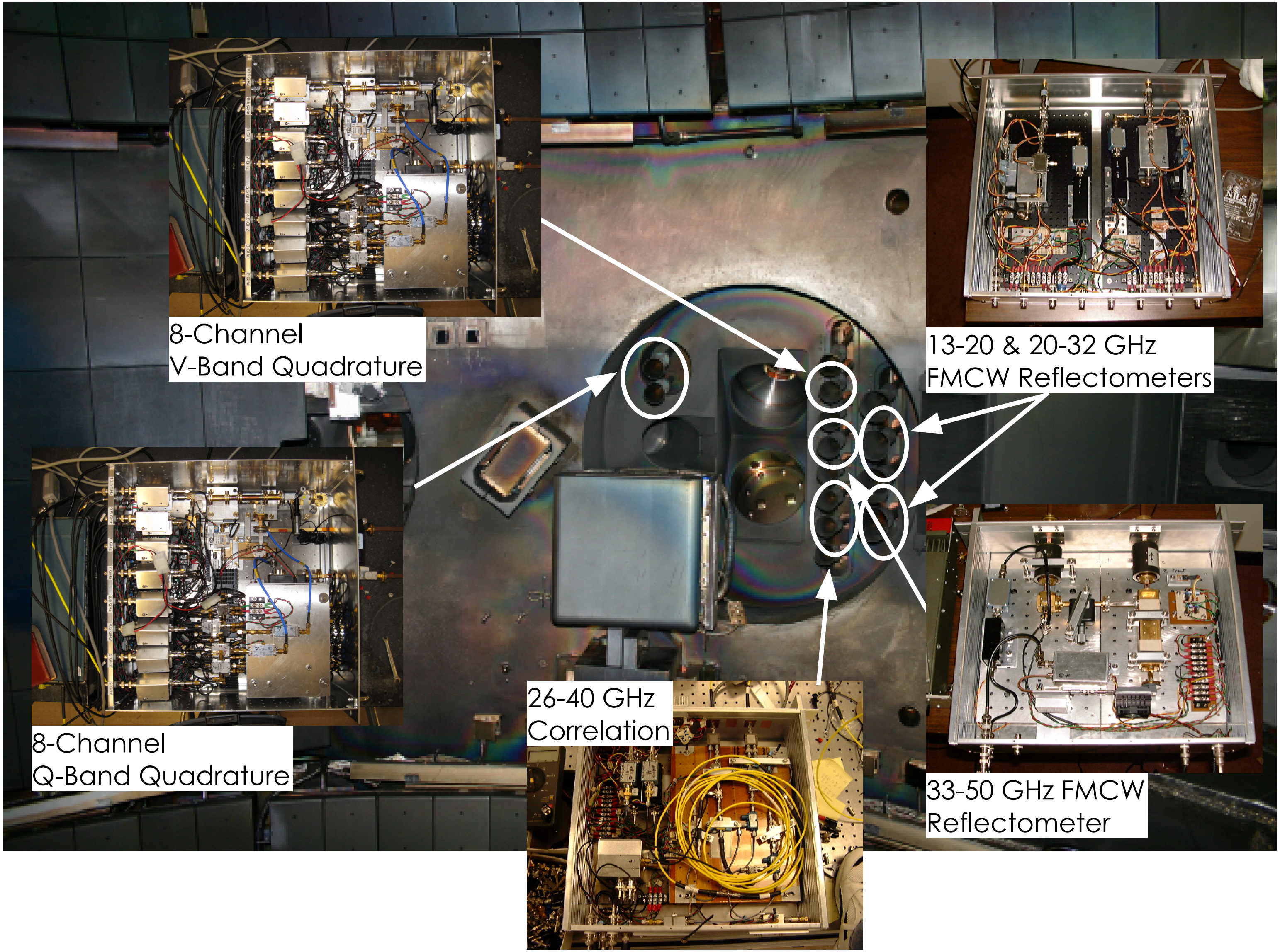
Warp grid created from $n_e(r)$.

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

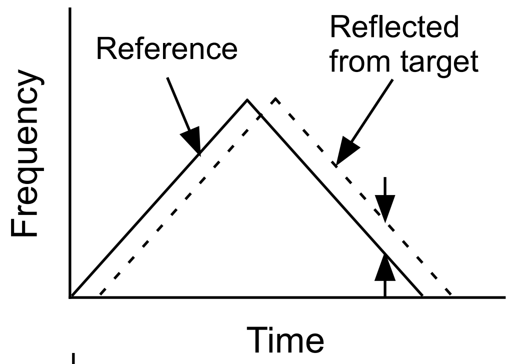


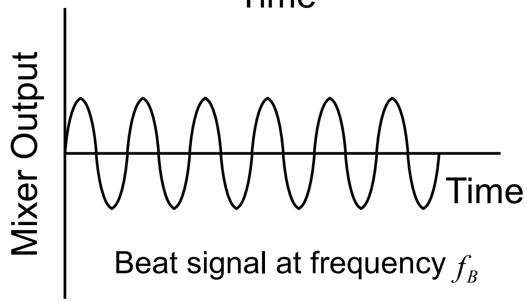


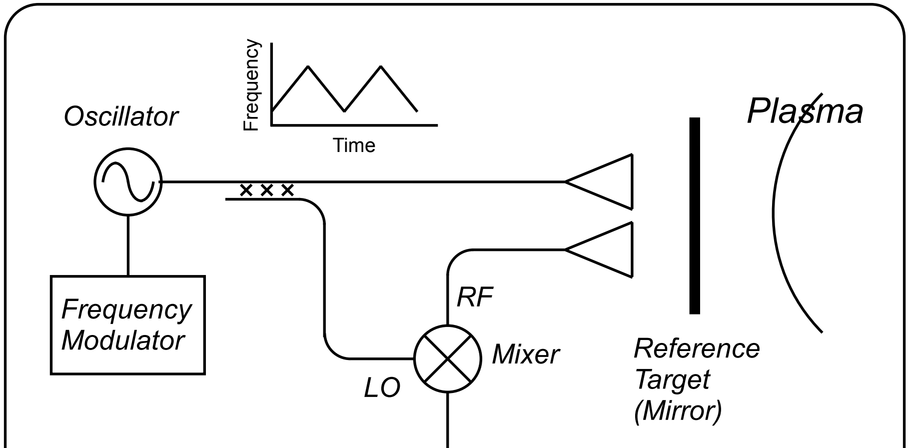
Millimeter-Wave Diagnostics for FY2010 Campaign



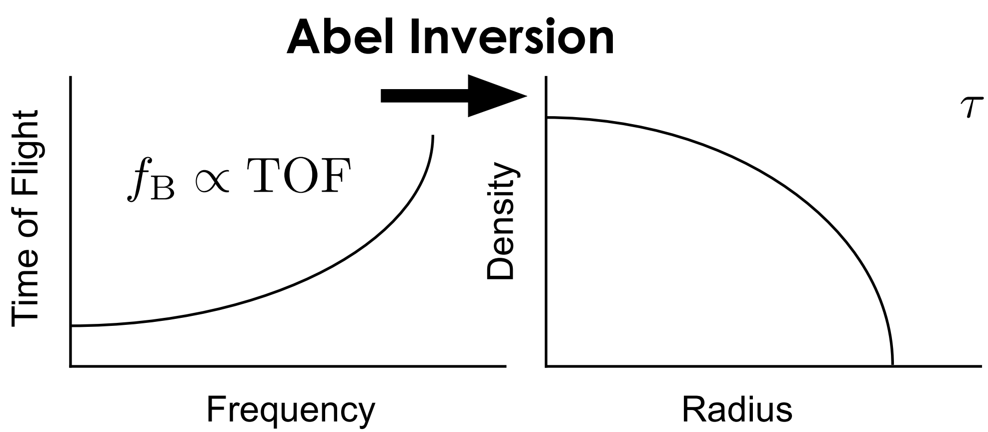
Review of FMCW (Profile) Reflectometry







Schematic of Homodyne FMCW Reflectometer



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

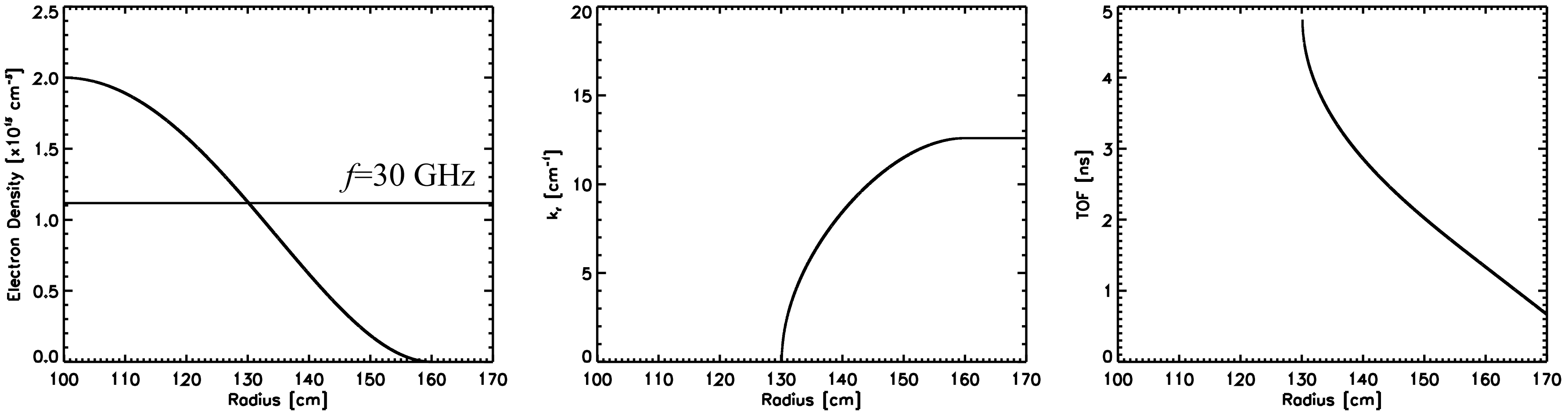
$$\tau(f) = \frac{1}{2\pi}\frac{d\phi}{df} = 2\int_{r_\mathrm{a}}^{r_\mathrm{c}(f)} \frac{1}{v_\mathrm{g}(f,x)}\,dx$$

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

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

Conceptual View of FMCW Backscattering (Single-Frequency Case)

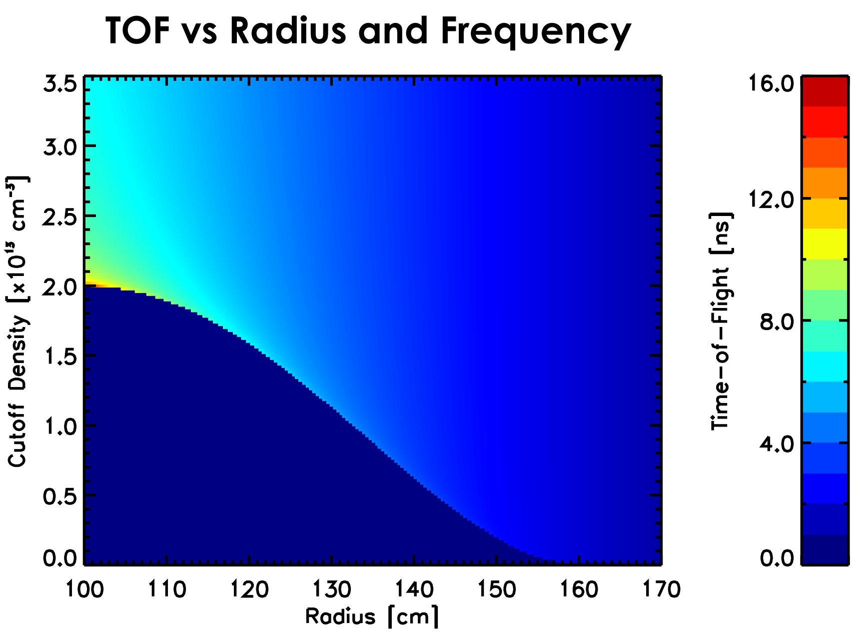
- Assume we know $n_e(R)$ from FMCW reflectometry. Consider wave-packet centered around f.

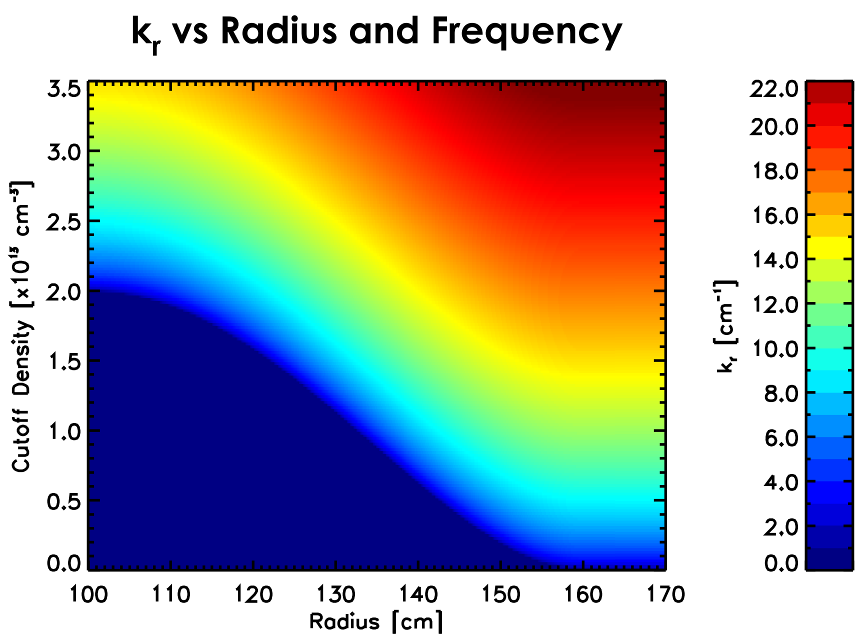


- Assume backscattered reflection from each point along path.
  - Bragg matching condition for backscattering: $k_r = 2\, k_0\, \mu(n_e(R), f)$
  - Time-of-flight (TOF) monotonically increasing towards cutoff.
  - Probes wavenumbers between $k = 2\, k_0 = 4\pi f/c$ (2x vacuum wavenumber) at edge and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

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.**