NSTX

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Reflectometry and Backscattering for Broad-k_r Microturbulence Measurements in NSTX

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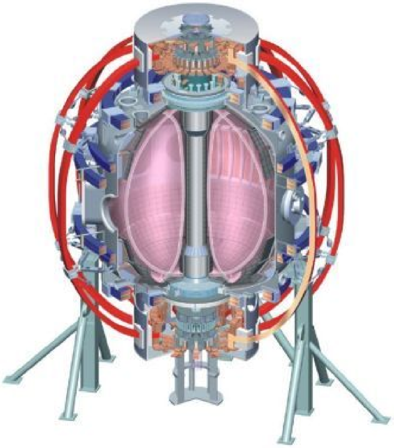

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Abstract

On NSTX, the unique combination of reflectometry hardware (FM-CW, fixed- frequency, and correlation reflectometers) is well-suited to turbulence measurements in both core and edge plasmas. Recently, the FM-CW reflectometers have been used as radial backscattering diagnostics for probing microturbulence over a broad range of radial wavenumbers (k_r~0-20 cm^{-1}). This new method utilizes the reflection from the cut-off layer to determine a detailed reconstruction of the density profile. Time-of-flight information is then used to map frequency-discriminated backscattered signals to radial locations away from the cutoff layer, allowing the visualization of turbulence in k_r vs R (major radius) space with excellent space and time resolution. Further details of the method will be demonstrated using modeled turbulence and the GPU-accelerated UCLA 1-D and 2-D FDTD full-wave codes. Initial measurements during the L-H transition show a steep drop in the turbulence intensity over a broad range of k_r and localized in a narrow spatial region around the edge transport barrier location.

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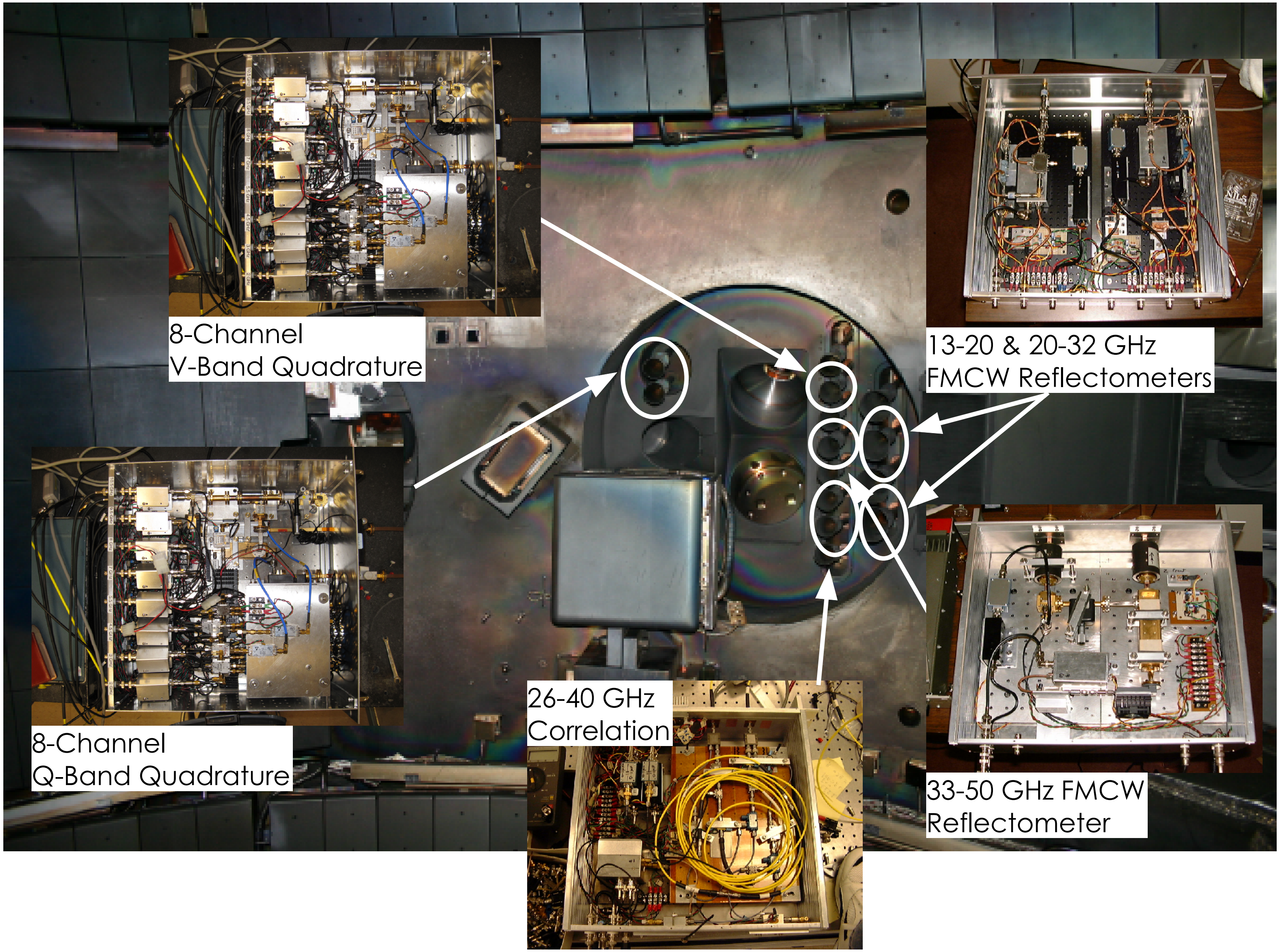
Poster Content

- Abstract
- Microwave diagnostics for turbulence measurements.
- Diagnostics on NSTX.
- Motivation for looking at higher k.
  - New technique: FMCW backscattering for k_r~0-20 cm^{-1}.
- Description of FMCW backscattering.
  - Mathematically akin to image warping from image processing.
- Application of FMCW backscattering on NSTX.
  - Turbulence suppression at the ETB location (L-H transition).
- Summary and future work.

Microwave Diagnostics for Turbulence Measurements

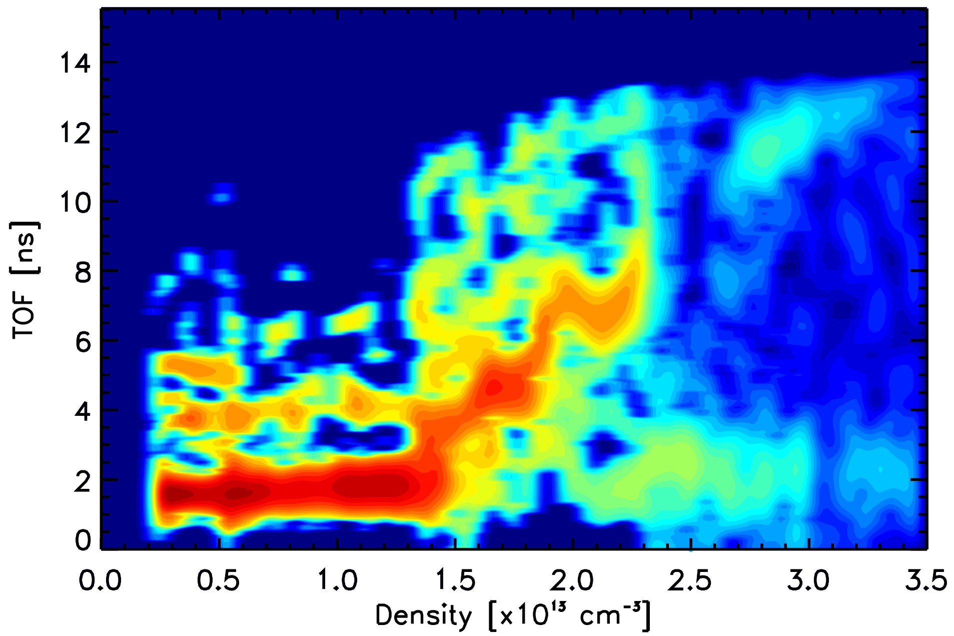
- Understanding micro-turbulence is a necessary step to controlling transport in fusion plasmas:
  - Instabilities cover a large range of wavenumbers and frequencies (GAMs, streamers, blobs, ITG, TEM, micro-tearing, ETG).
  - Some instabilities can feed back to the modify the equilibrium profiles (density, temperature, flows, etc.).
- New microwave diagnostics on NSTX enhance our ability to make detailed turbulence and profile measurements.
  - Ultra-fast swept FMCW reflectometers coupled with new analysis techniques:
    - > Electron density profiles with 7 μs time resolution
    - > Sub-millisecond turbulence radial correlations
    - > High-k_r back-scattering
  - 2-channel poloidal correlation reflectometer:
    - > Turbulence flow
    - > Poloidal correlations
  - 16-channel fixed-frequency reflectometers:
    - > Detailed profile of turbulence fluctuation level
- Full-wave codes (synthetic diagnostics) with GPU acceleration.

Millimeter-Wave Diagnostics for FY2010 Campaign



Motivation for Looking at Broad-k_r Fluctuations

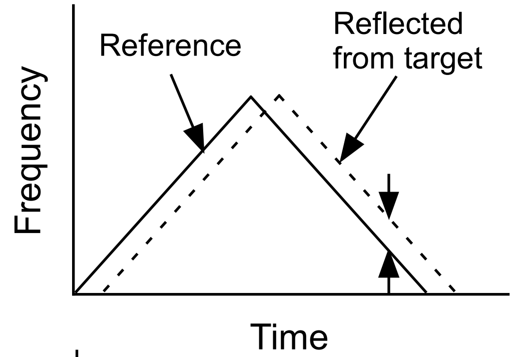
- **Experimental evidence that broad-k_r turbulence can be measured with good time and spatial resolution.**

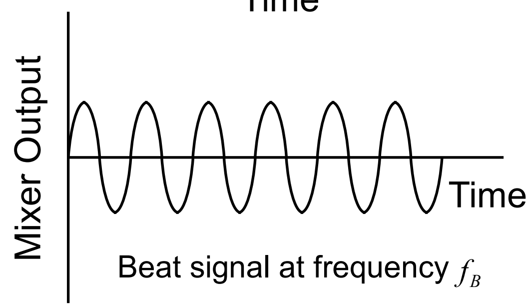


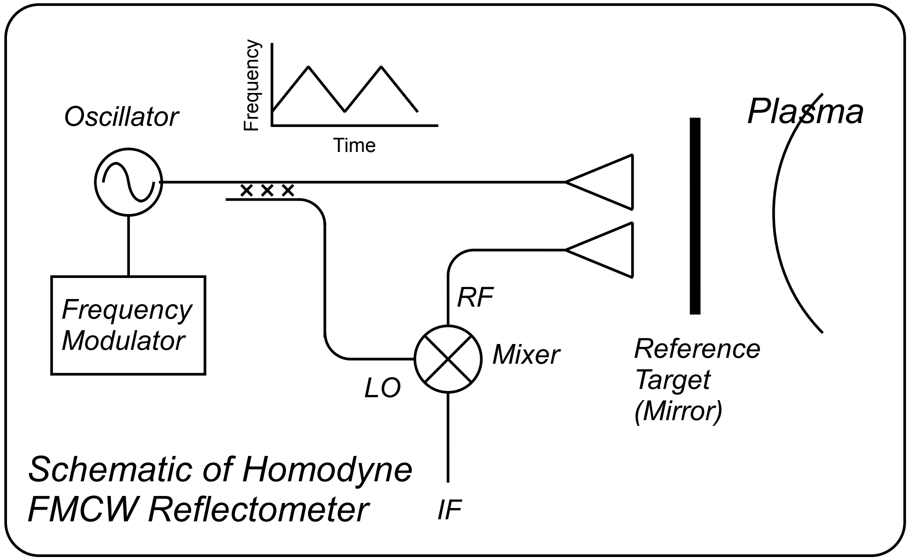
- FMCW radar image.
  - > 13-53 GHz coverage (2.1×10^{12} to 3.5×10^{13} cm^{-3}).
  - > Maximum repetition rate of 7 μs/sweep.

- **Other empirical reasons for wanting broad wavenumber spectrum:**
  - More sensitive measurement of turbulence a higher k.
    - > Better isolated from changes in the background profile.
    - > Easier to track modulation of turbulence.
  - Correlation lengths.
    - > Turbulent eddies and large coherent structures (streamers).

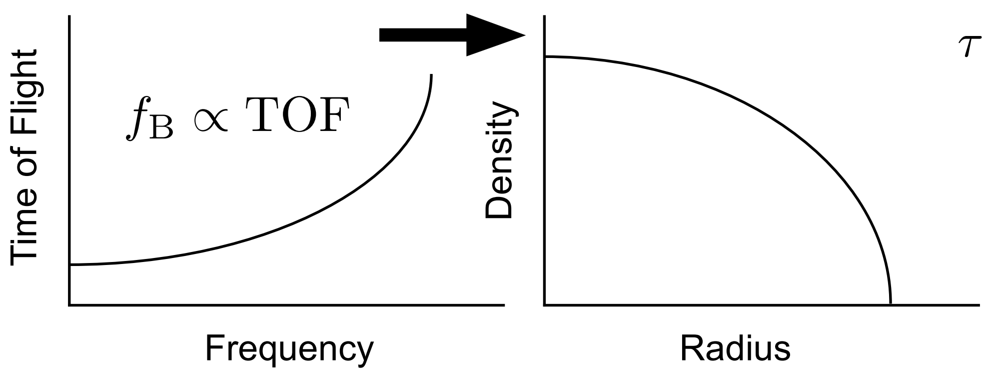
Review of FMCW (Profile) Reflectometry







Abel Inversion



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

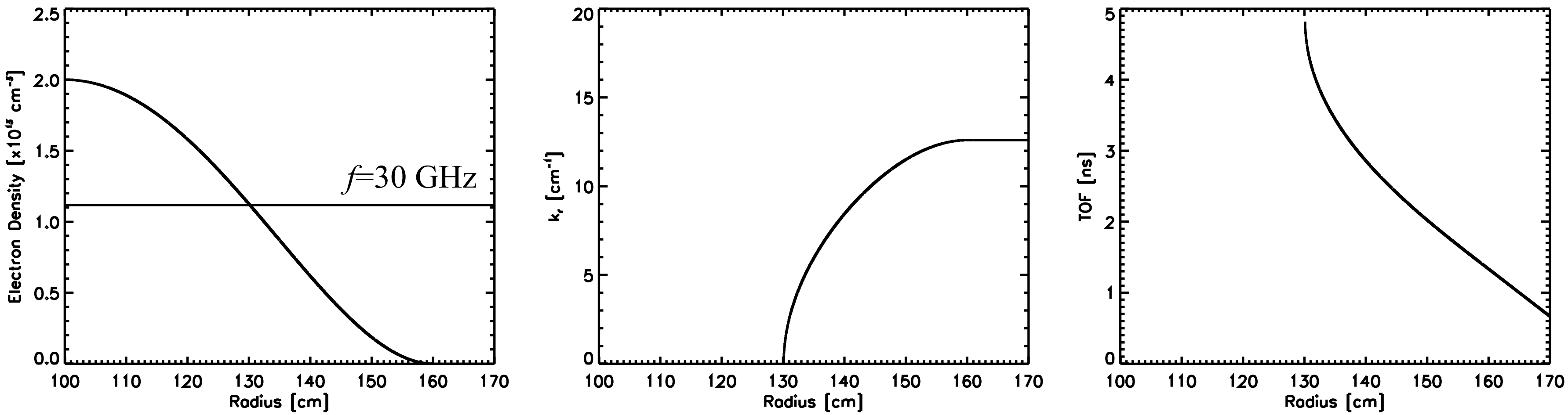
$$\tau(f) = \frac{1}{2\pi}\frac{d\phi}{df} = 2\int_{r_a}^{r_c(f)} \frac{1}{v_g(f,x)} dx$$

$$= \frac{2}{c}\int_{r_a}^{r_c(f)} \left(1 - \frac{f_p^2(x)}{f^2}\right)^{-1/2} dx$$

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

Conceptual View of FMCW Backscattering (Single-Frequency Case)

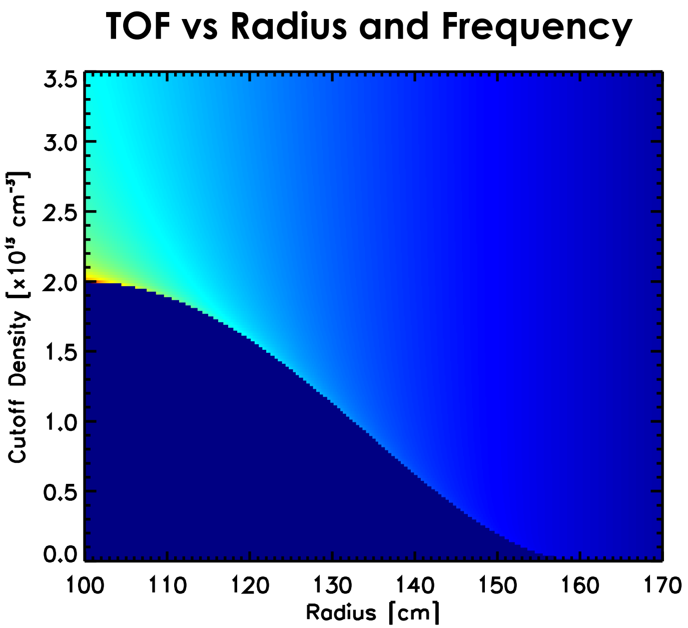
- Assume we know $n_e(R)$ from FMCW reflectometry. Consider wave-packet centered around f.

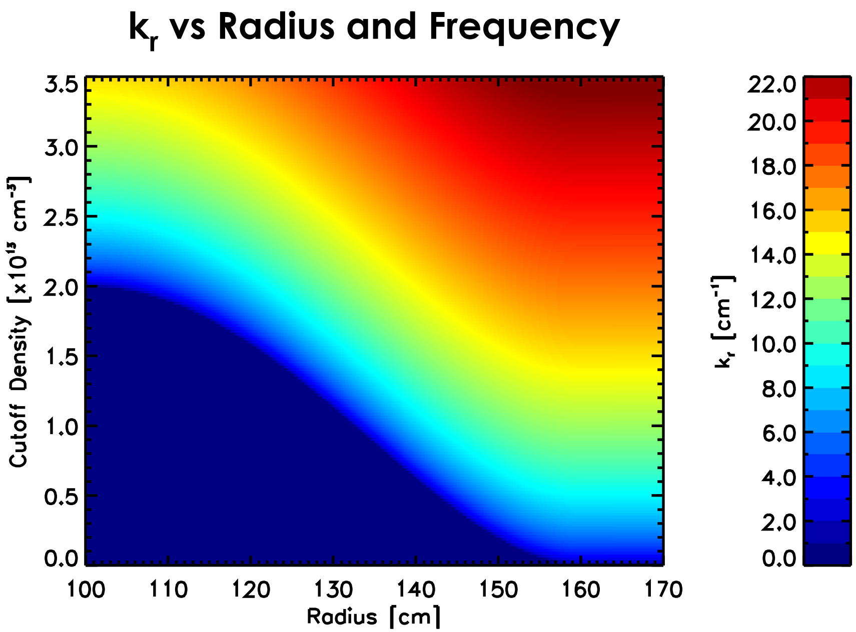


- Assume backscattered reflection from each point along path.
  - Bragg matching condition for backscattering: $k_r = 2\, k_0\, \mu(n_e(R), f)$
  - Time-of-flight (TOF) monotonically increasing towards cutoff.
  - Probes wavenumbers between $k = 2\, k_0 = 4\pi\, f/c$ (2x vacuum wavenumber) at edge and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

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

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

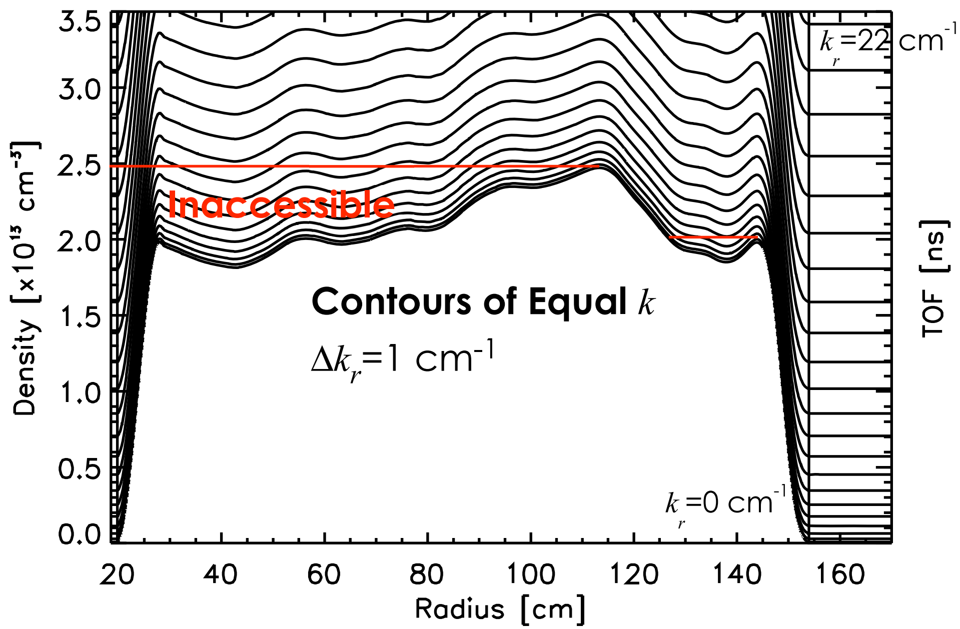




- **Provides a signal intensity map from (τ, f) to (k_r, R).**
  - One-to-one mapping.
  - If one knows $n_e(R)$, this mapping must be unique (stated here without proof).
- **Method is similar to conventional 180° collective backscattering, but**
  - Scattered/reflection location is discriminated by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



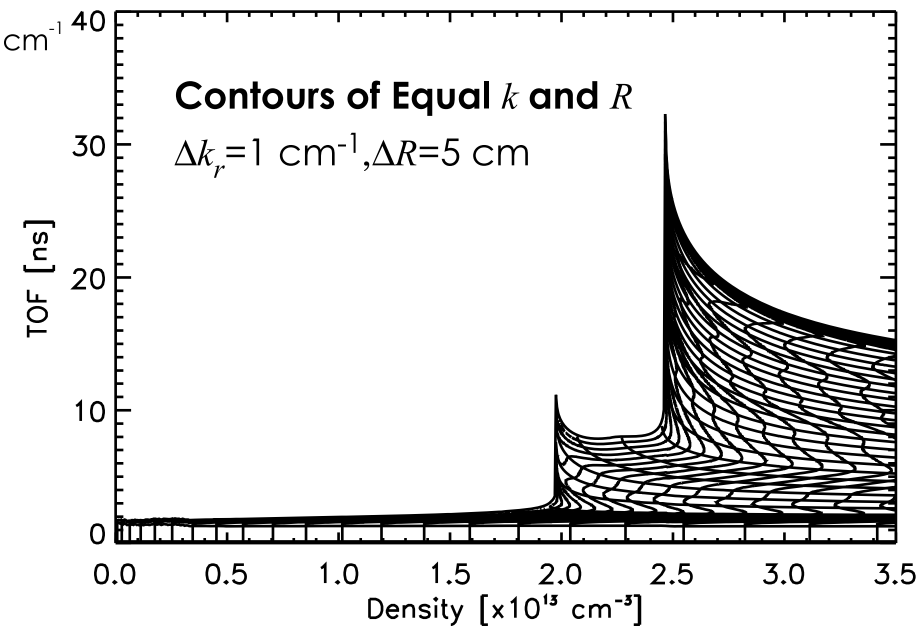
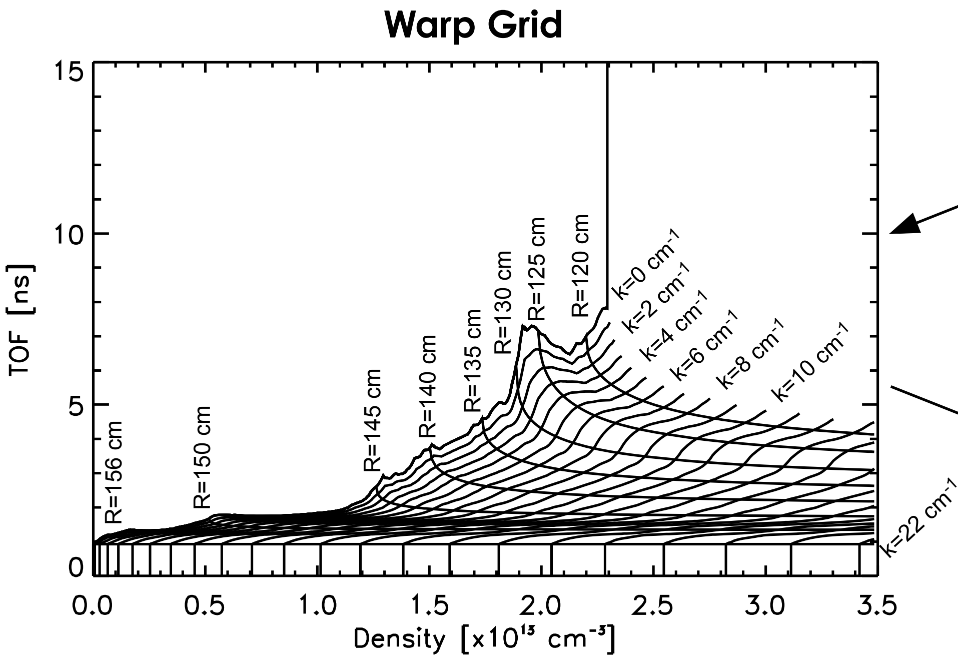
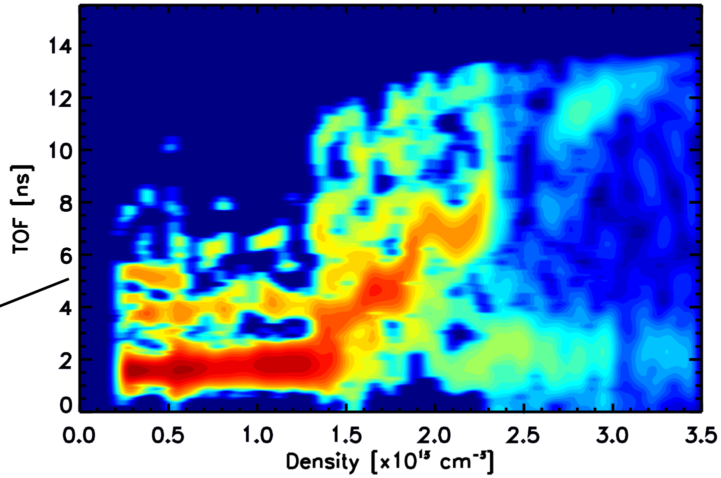
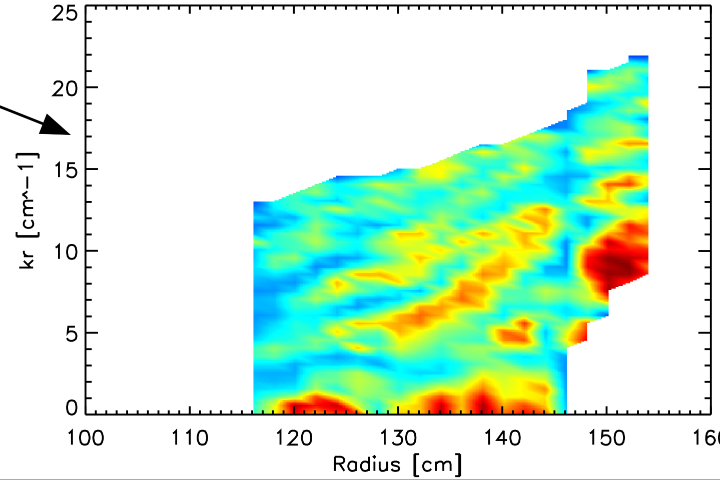


Image Processing Analog: Image Warp

- **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.



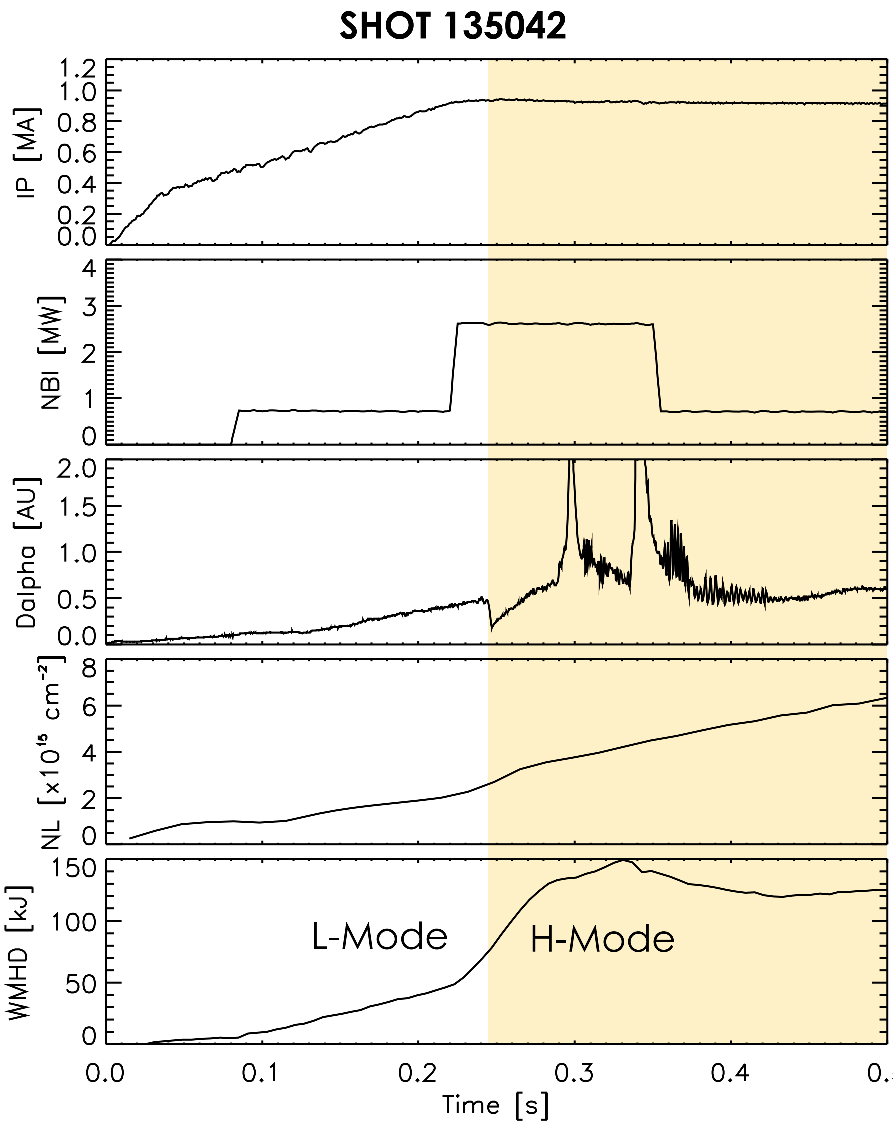


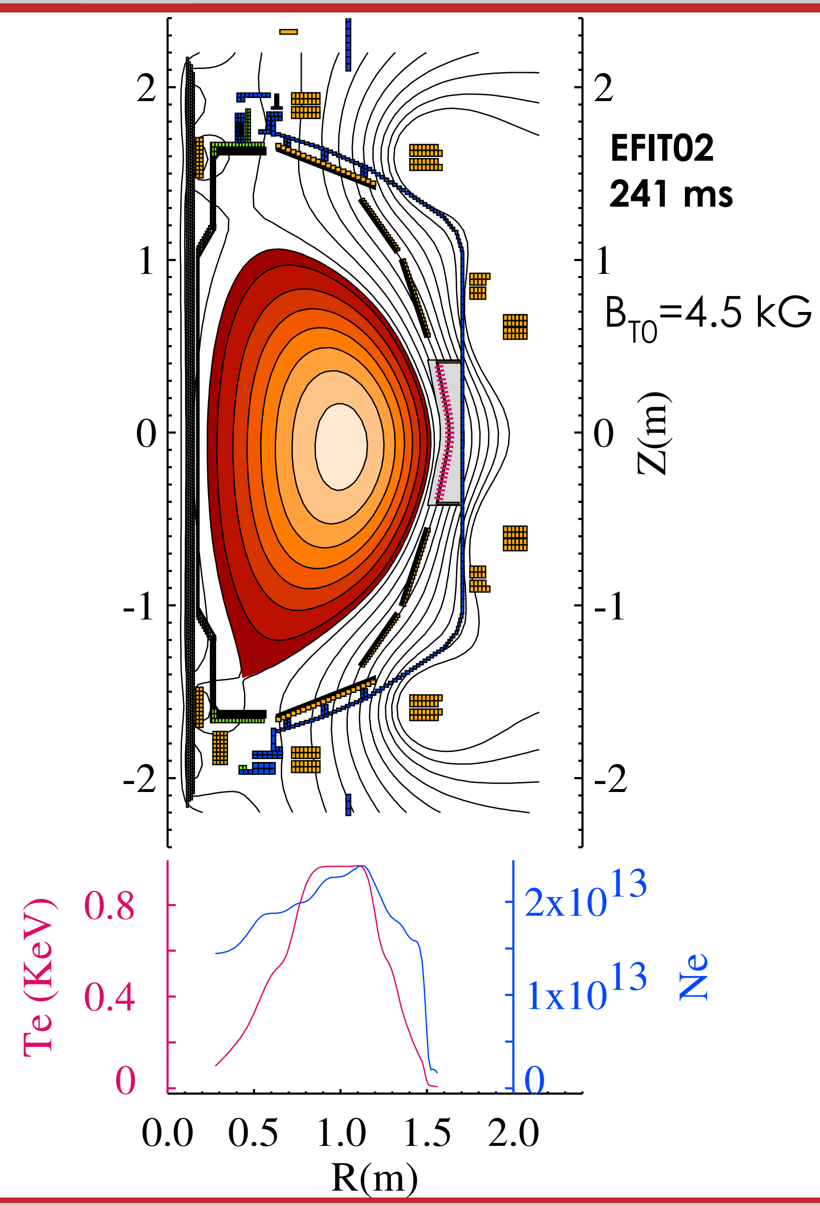


Signal Processing Technique

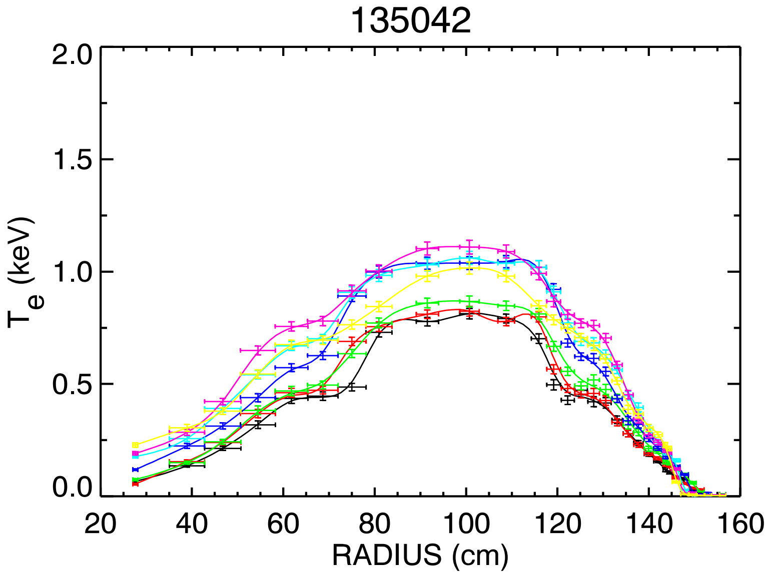
- **Prescription for creating backscattered signal intensity image in (k_r,R).**
  - Create (τ,f) image to determine TOF curve for profile inversion.
  - Abel invert $\tau(f)$ to create $n_e(R)$.
  - Using $n_e(R)$, calculate (τ,f) points corresponding to a (k_r,R) grid.
  - Since $f(t)=f_0+\alpha\, t$, 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.**

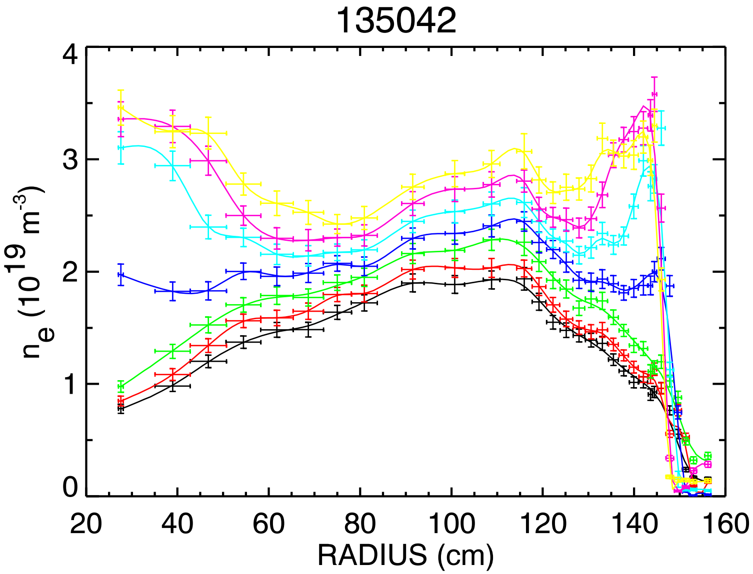
Target: NB-Heated Discharge with L-H Transition

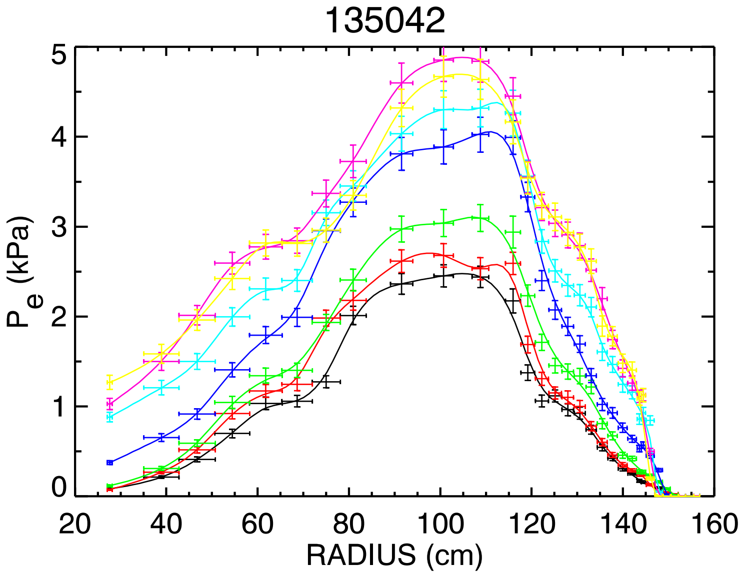


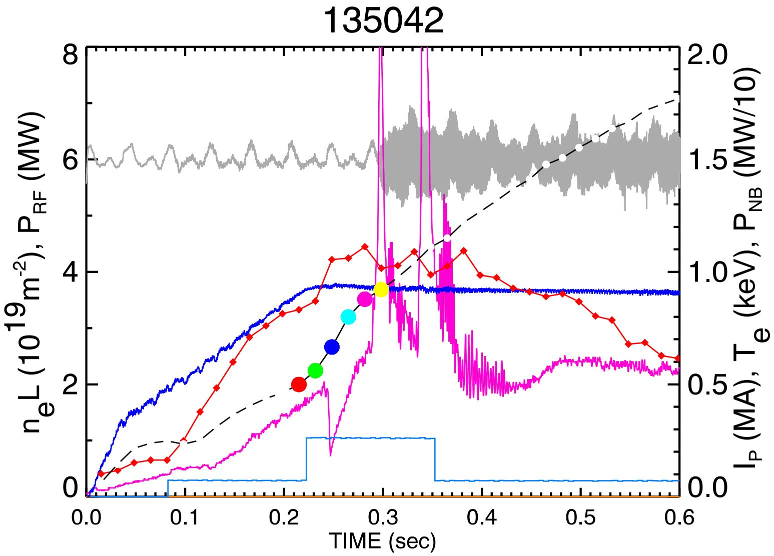


NBI-Heated Discharge Profiles



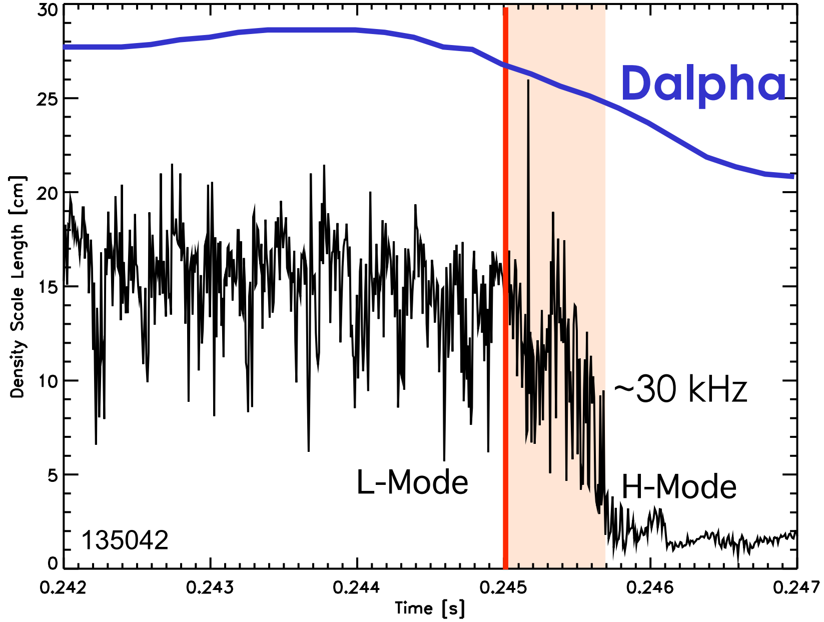




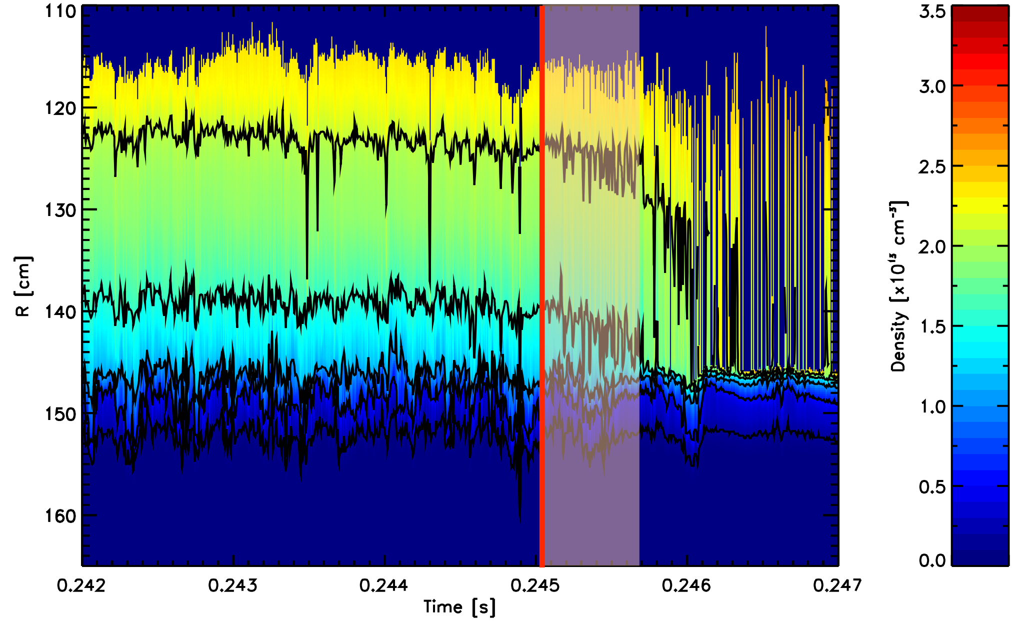


Fast Density Profile Evolution Near the L-H Transition

Electron Density Scale Length
(at n_e=1.0-1.5x10^{13} cm^{-3})

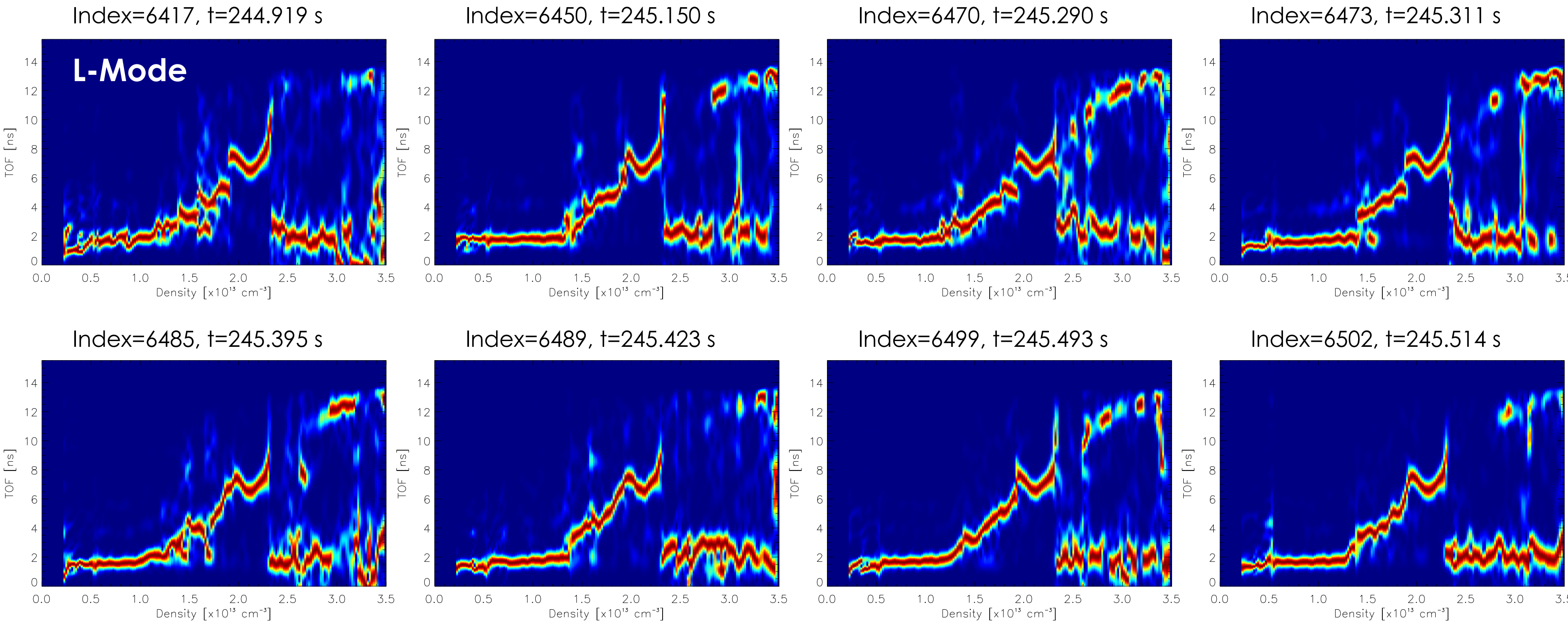


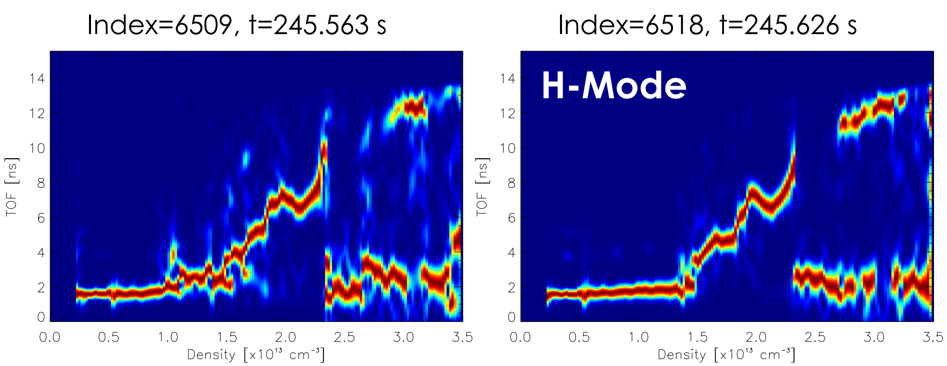
Electron Density Contours



- Fast evolution of electron density profile near L-H transiton from FMCW reflectometry (Δt=7 μs).
  - Edge gradient begins to increase.
  - During t=0.2452-0.2457 s, gradient in the density range 1.0-1.4x10^{13} cm^{-3} dithers.
  - Rapid oscillations in the density gradient at ETB location.

Radar Images Near L-H Transition

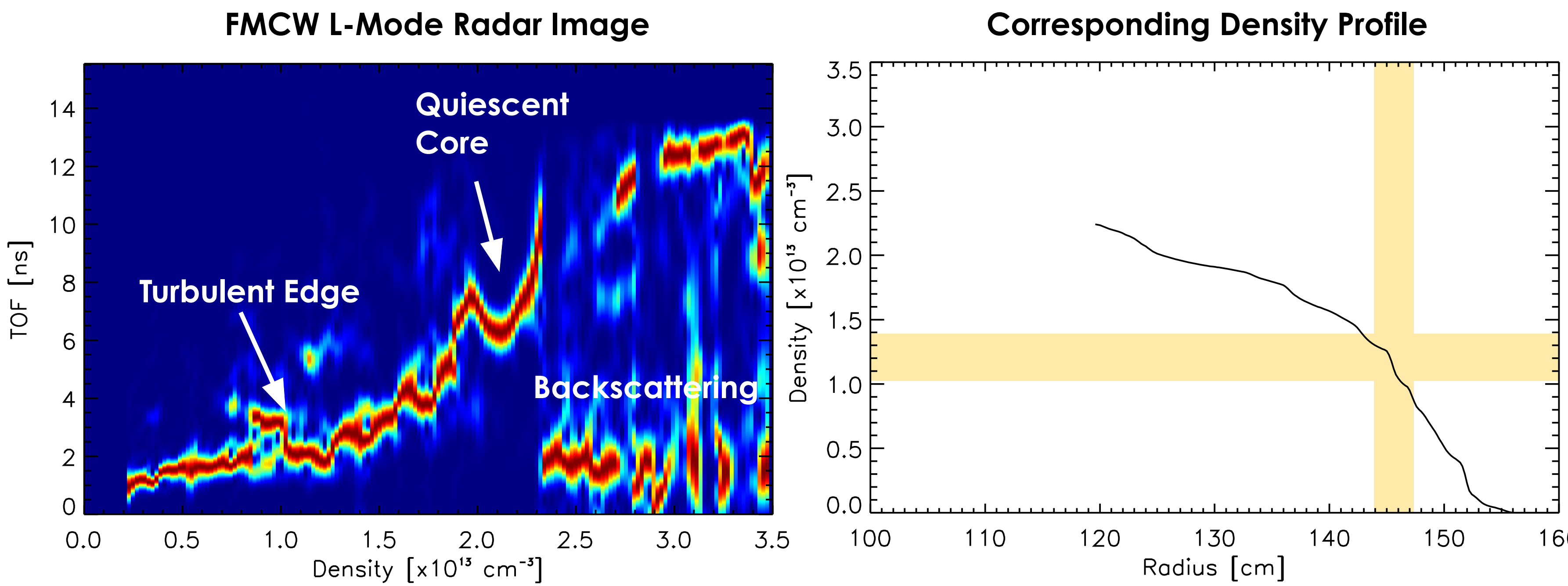




- **H-mode edge established at ~245.15 s.**
  - Steep edge gradient below ~1×10^{13} cm^{-3}.
  - Several oscillations between steep and shallower gradient for the density range ~$1\text{-}1.4\times10^{13}$ cm^{-3} until ~245.626 s.
- **During 245.15-245.626 s, both GPI and 30 GHz reflectometer show that edge turbulence is not yet fully suppressed.**

ETB Location at R~146 cm

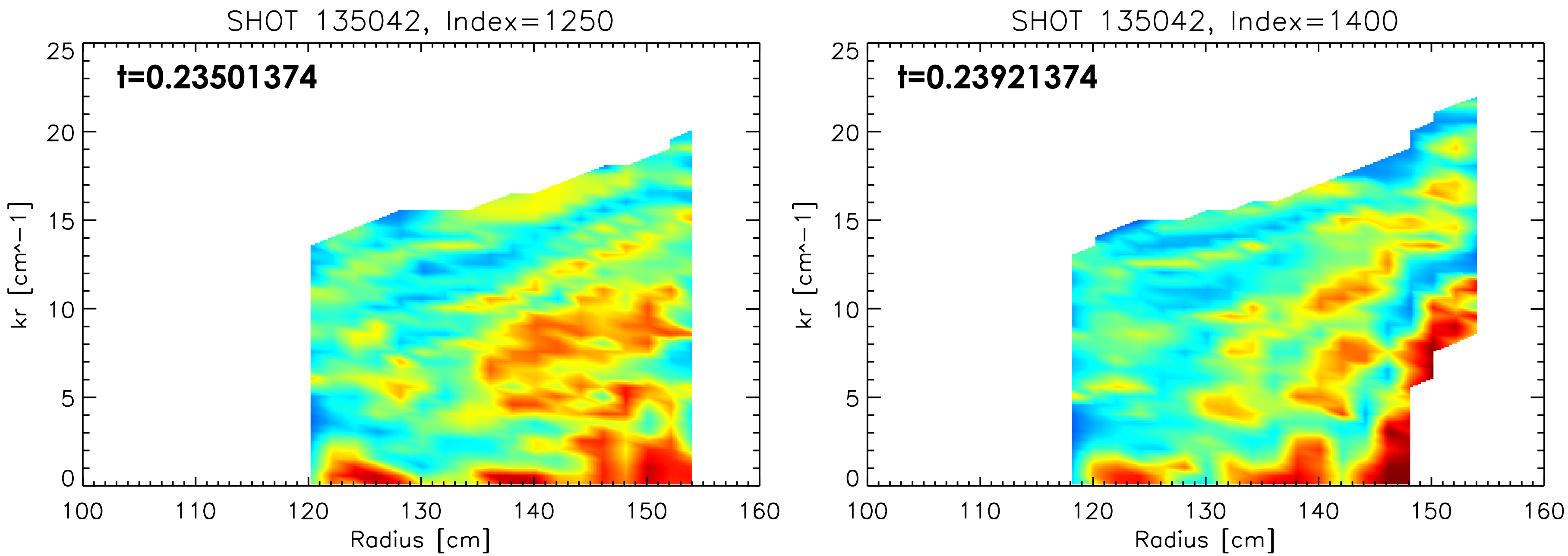
- ETB location identified using gradient oscillations (1.0-1.4x10^{13} cm^{-3}).



- ETB radius centered at ~146 cm at the L-H transition.

k_r Spectrum vs Radius in L-Mode Phase

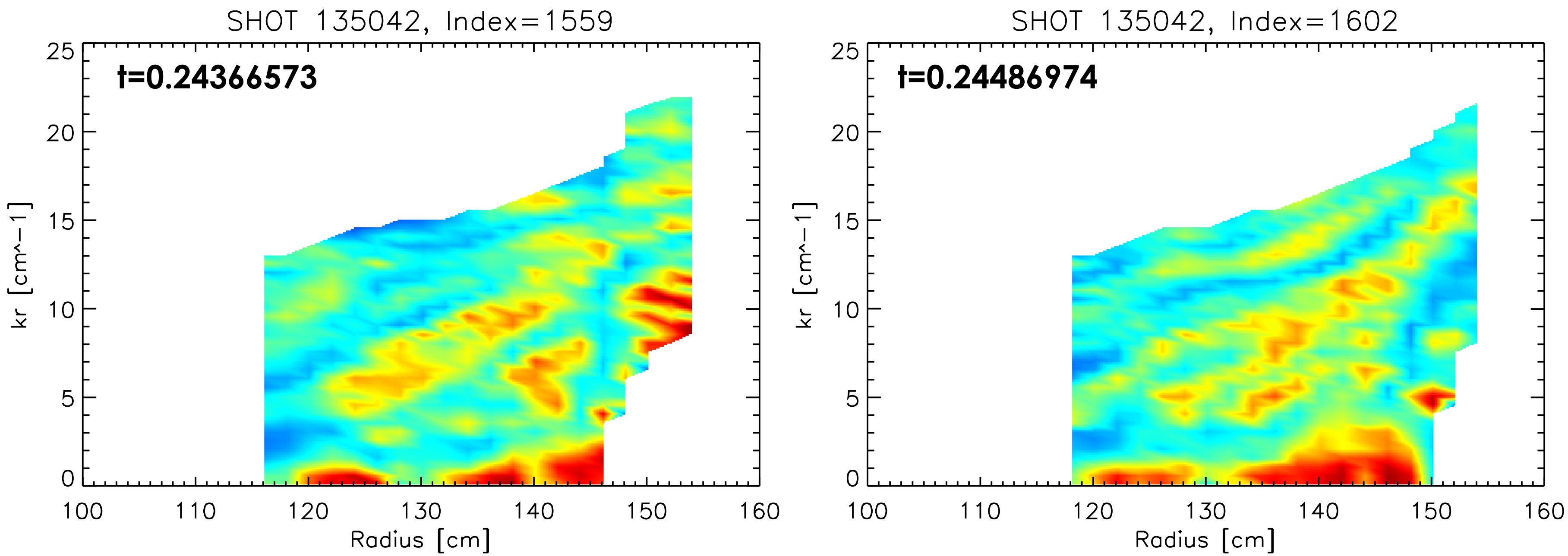
- **Spectra from well before the L-H transition (~0.245 s).**



- **k_r spectrum becomes narrower towards core.**
- **Averaging over 4 sweeps (28 μs).**

k_r Spectrum vs Radius Just Before the L-H Transition

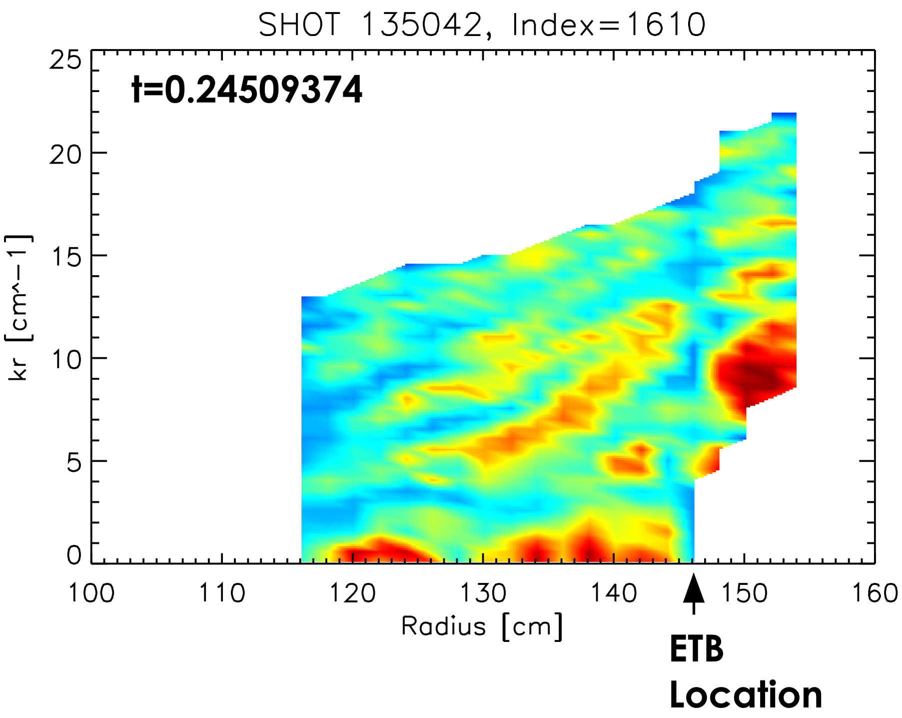
- Spectra just before the L-H transition (~0.245 s).

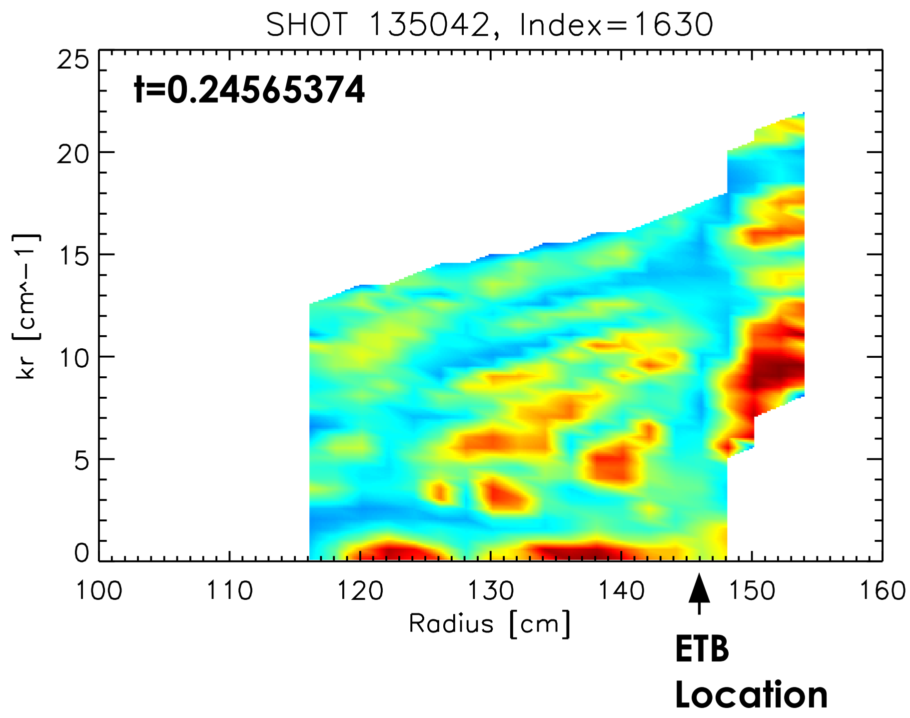


- Recall that ETB occurs at radial location of R~146 cm.

k_r Spectrum vs Radius Just After the L-H Transition

- **Spectra just after the L-H transition (~0.245 s).**

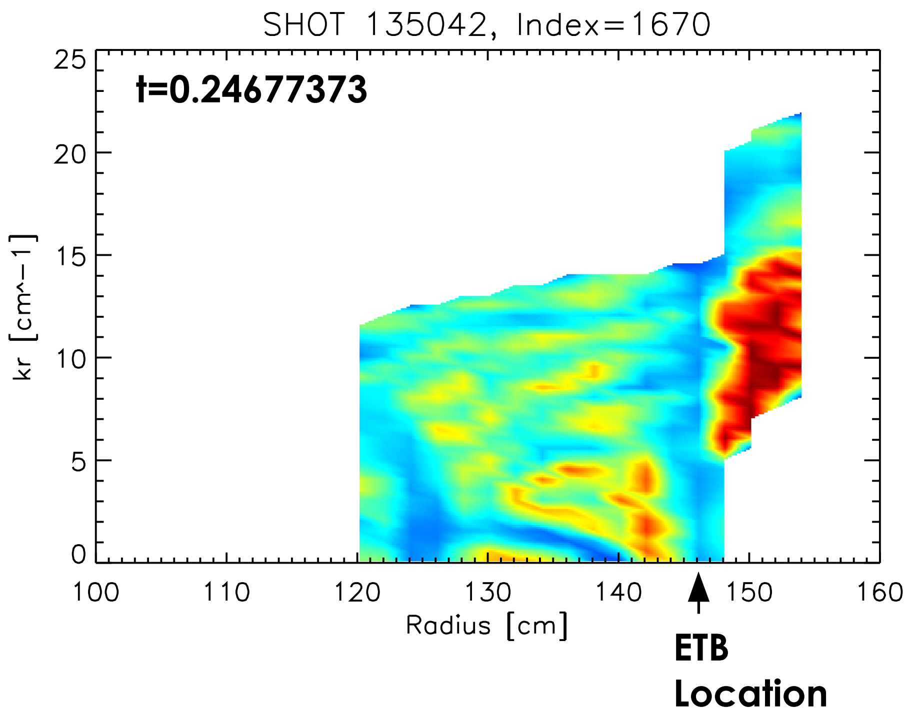


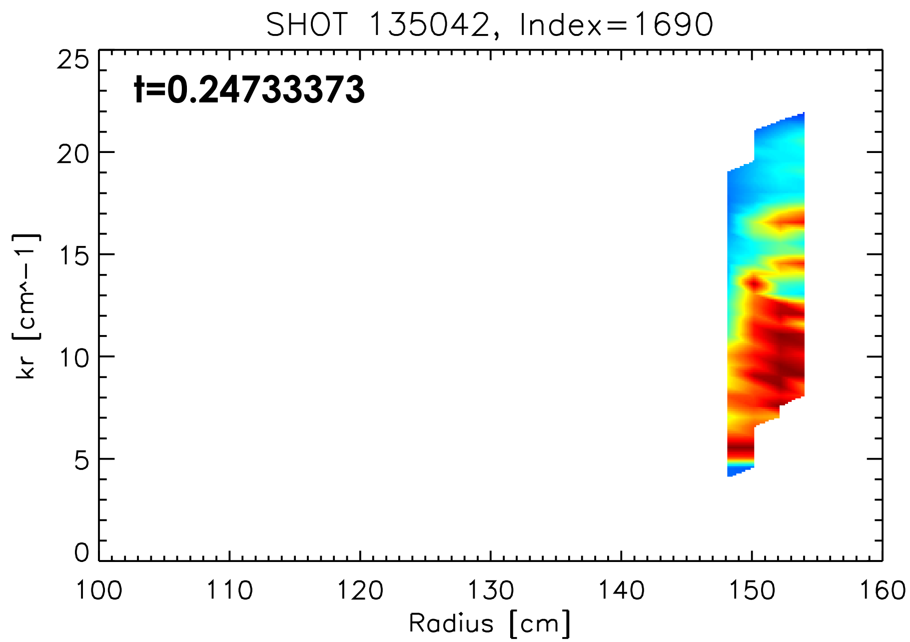


- **Well develops in the k_r vs R spectrogram at ETB location (R~146 cm).**
- **Large edge intensity (static) due to sharp edge density "ear".**

k_r Spectrum vs Radius After the L-H Transition

- Spectra after the L-H transition (~0.245 s).





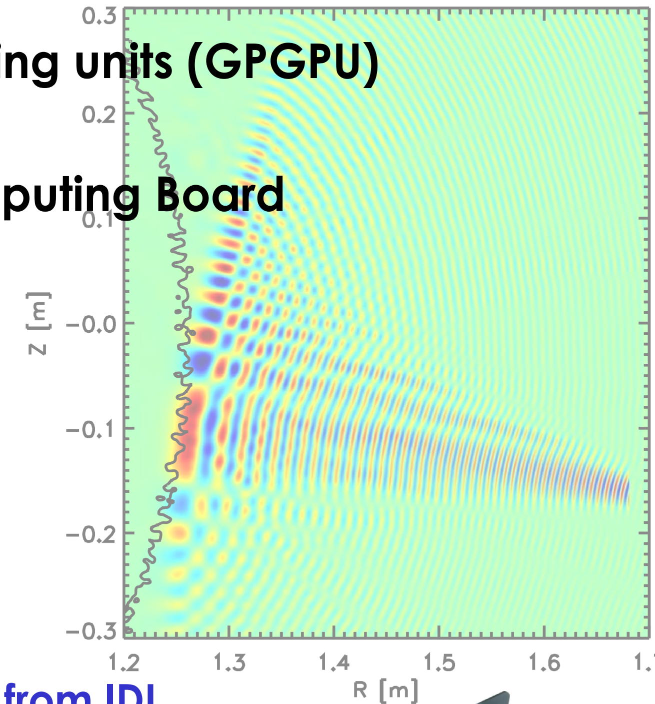
- Well in the k_r vs R spectrogram deepens.
- Accurate reconstruction of interior density profile lost (~1.7 ms after L-H transition) due to growth of edge density "ear".

Conclusions and Future Work

- **New method for visualing turbulence in k_r vs R space:**
  - Utilizes data from existing FMCW reflectometers on NSTX.
    - > Extends usefulness of reflectometer data to situations where cutoff does not exist.
  - For L-mode low density plasmas, access over a large fraction of minor radius.
  - Evolution of turbulence wavenumber spectra with spatial and time resolution.
- **Initial look at L-H transition in NSTX:**
  - Intensity "well" in k_r vs R space coincident with L-H transition at exactly the ETB location.
  - Data analysis technique is still evolving, but results look very compelling.
- **Future work will involve obtaining quantitative results.**
  - k_r spectral shape:
    - > Radial correlation lengths.
    - > Evolution of turbulent eddies and coherent structures (e.g. streamers).
    - > Need to account for power variation vs frequency of microwave source.
  - Simulations using 1-D and 2-D full-wave codes:
    - > Use either FMCW or pulse source.
    - > GPGPU-assisted computation.

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



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