# Analysis of Fast-ion $D_\alpha$ Data from NSTX

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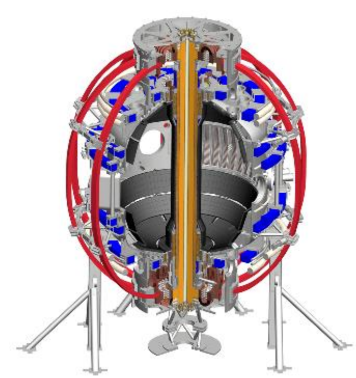


# INTRODUCTION

- **Numerous fast ion instabilities have significant effect on beam-ion confinement at NSTX:**
  - **Abrupt Large Events (ALE)**
  - **Energetic Particle Modes (EPM)**
  - **TAE modes and TAE avalanches**

- **In a recent study[1] a database of ~360 time instances from ~170 shots (year 2010) was assembled. Correlations between typical parameters relevant for beam ion confinement were established:**

$\langle\beta_{fast}\rangle / \langle\beta_{total}\rangle$ $V_{fast} / V_A$ $\delta S/S$ $\delta B/B$

- **We extend this database with data from the vertical Fast Ion $D_\alpha$ (FIDA) diagnostic, and corresponding FIDASIM[2] simulations which assume no beam ion loss.**

1) E. Fredrickson *et al.*, Nucl. Fusion 54 (2014) 093007

2) W. Heidbrink *et al.*, Commun. Comput. Phys. 10 (2011) 716.

# Fredrickson classified the different types of instabilities

Nucl. Fusion 54 (2014) 093007 E.D. Fredrickson *et al*

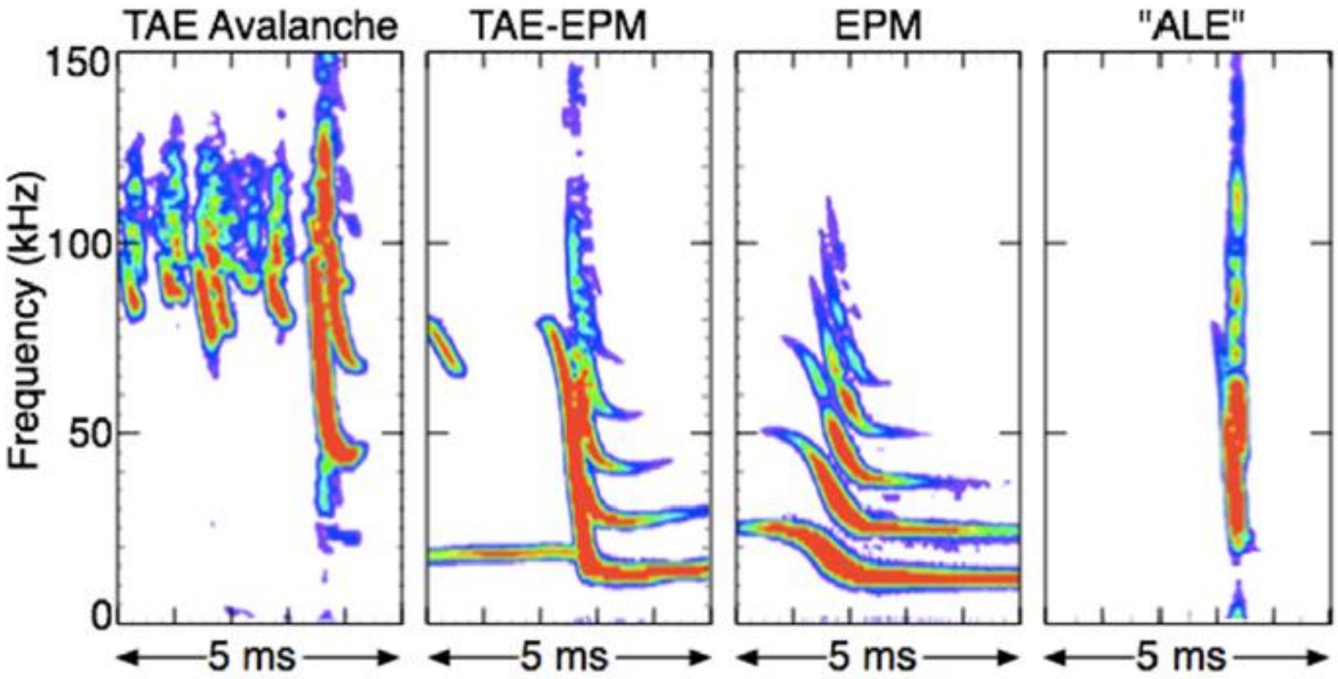



**Figure 2.** (*a*) Spectrogram showing a TAE avalanche, (*b*) spectrogram showing a hybrid TAE avalanche and EPM, (*c*) spectrogram of an EPM avalanche and (*d*) spectrogram of an ALE.

# Fredrickson found where the various instabilities occur in parameter space

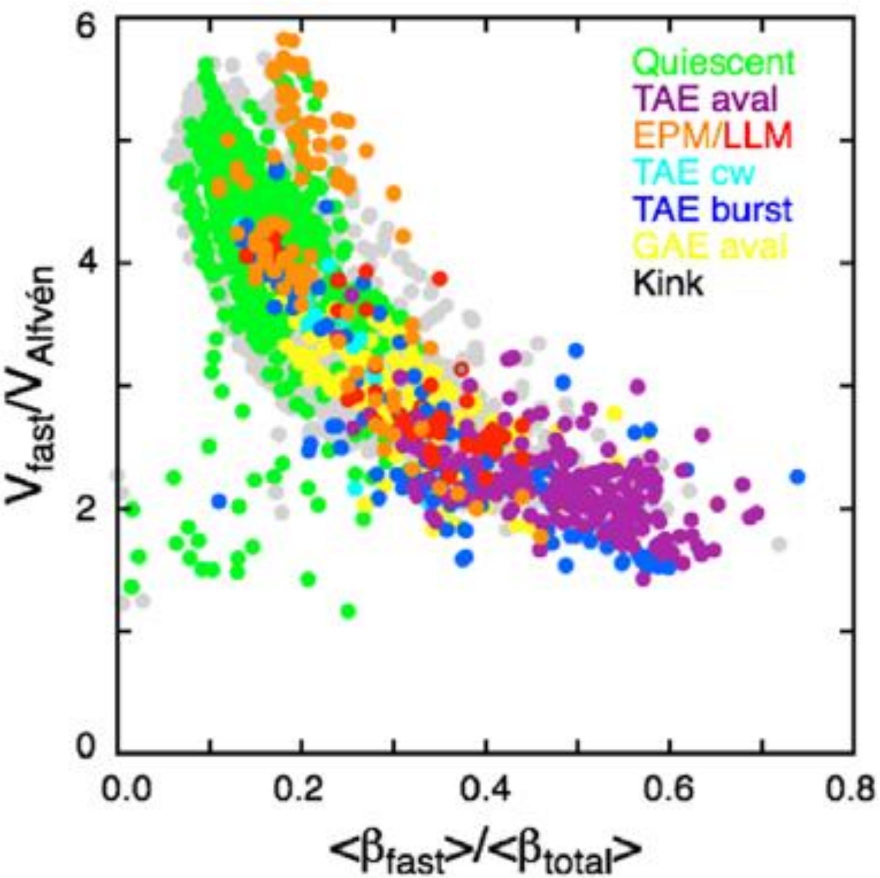
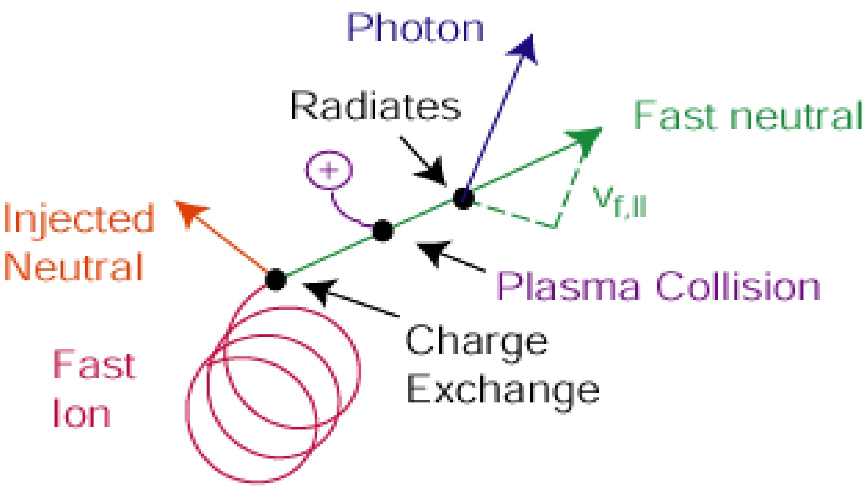



**Figure 3.** Existence plot for a variety of MHD activities.

E. Fredrickson *et al*., "Parametric dependence of fast-ion transport events on the NSTX"," Nucl. Fusion 54 (2014) 093007

- **Avalanches & ALEs require large $\beta_{fast}$**
- **Quiescent conditions at higher $n_e$**

# FIDA is an application of Charge Exchange Recombination Spectroscopy

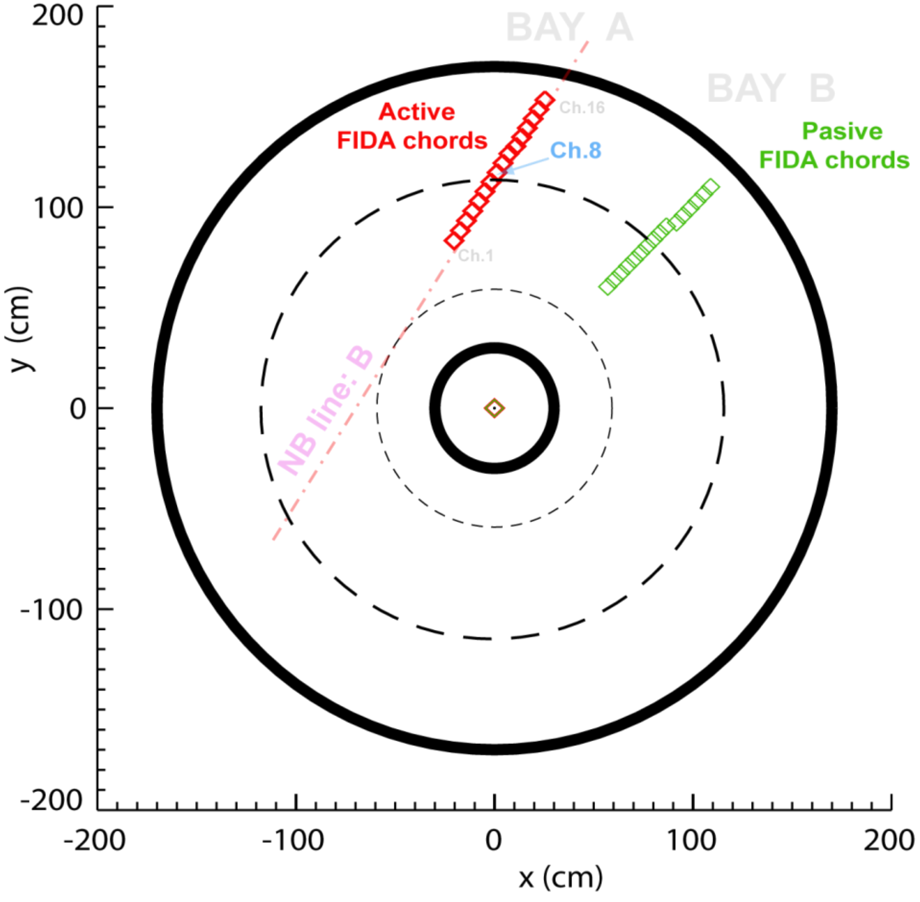



W. Heidbrink, Rev. Sci. Instrum. **81** (2010) 10D727

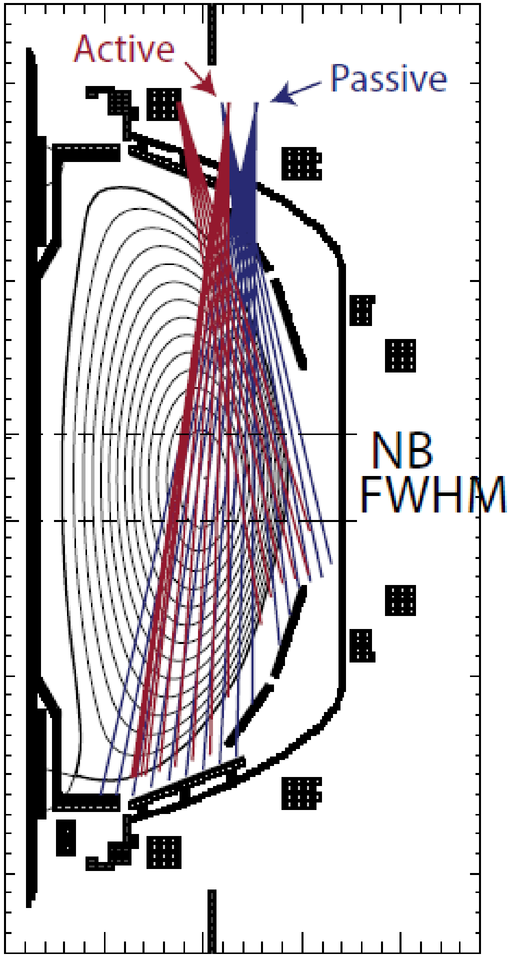
1. **The fast ion exchanges an electron with an injected neutral**
2. **Neutrals in the n=3 state relax to an equilibrium population; some radiate**
3. **The Doppler shift of the emitted photon depends on a component of the fast-ion velocity**

# Vertical FIDA data were routinely archived in 2010

## Plan view

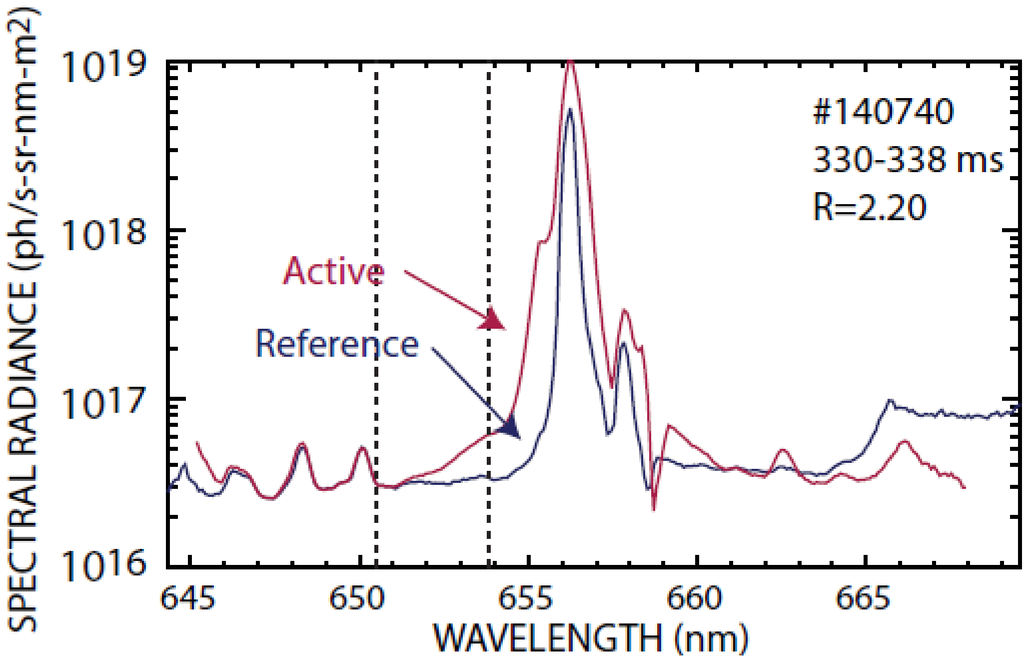



## Elevation



# Construction of the Database

# Use the net signal on the blue-shifted side

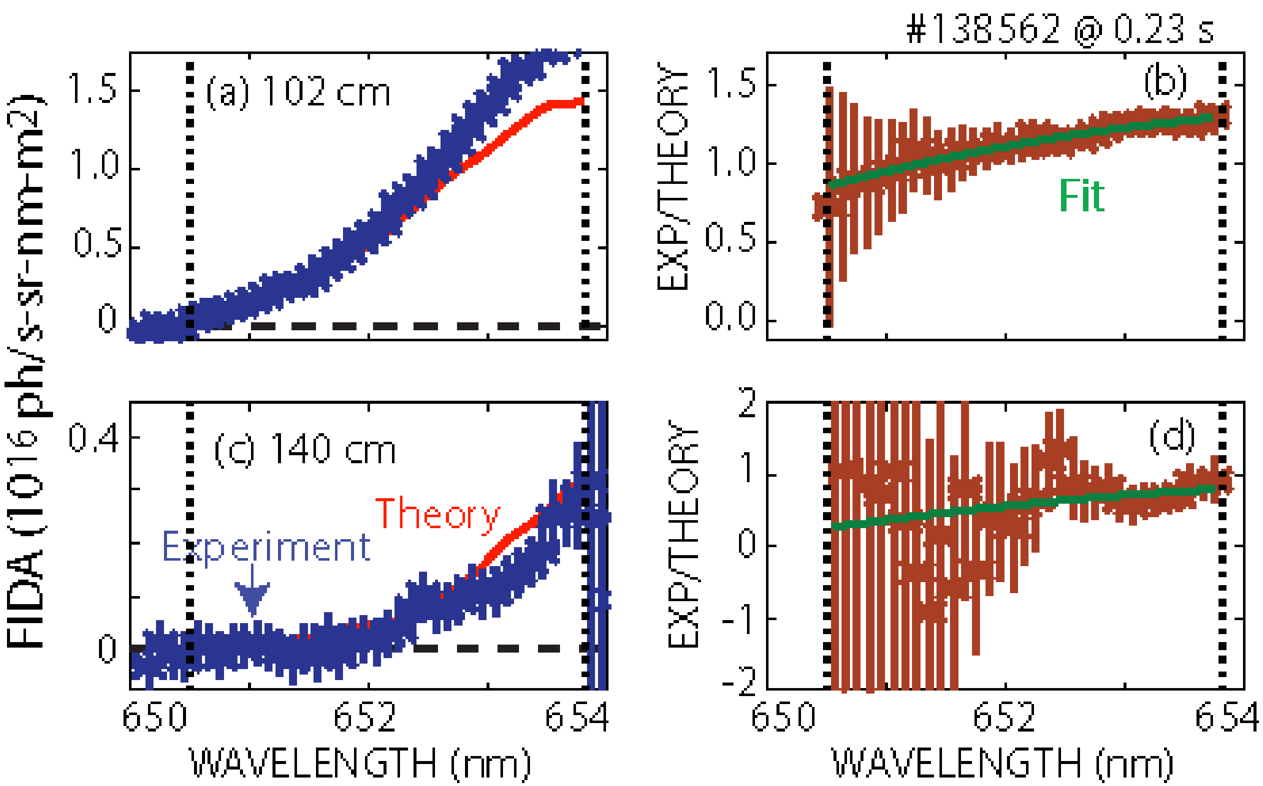



- The FIDA light is the difference between the active and passive views
- Wavelengths of interest are between the dotted lines
- The red-shifted side is ignored

# Use NUBEAM & FIDASIM to predict the signal

- **Beam ion distribution functions $f_b$ is calculated with TRANSP using classical modeling with identical parameters for all shots, including:**
  - ADAS atomic physics data
  - N=20,000 Monte Carlo particles
  - $f_b$ is averaged over 20ms around the time of interest (TOI)
  - External neutral density $N_0$= $5x10^{10}$ $cm^{-3}$
- **16 FIDA spectra are calculated with the FIDASIM code for each of the ~360 times of interest. In subsequent analysis, beam ions with energy component along the s-FIDA line of sight in three energy bands are considered:**
  - Full energy range $E_1$: 11.5-68.0 keV, $\lambda$=650.5-653.8nm
  - Low energy range $E_2$: 11.5-31.3 keV, $\lambda$=652.3-653.8nm
  - High energy range $E_3$: 31.3-68.0 keV, $\lambda$=650.5-652.3nm
- **Specialized software tools were written to facilitate the massive data preparation for TRANSP and FIDASIM modeling and data analysis.**

# Compare experimental & theoretical spectral shapes



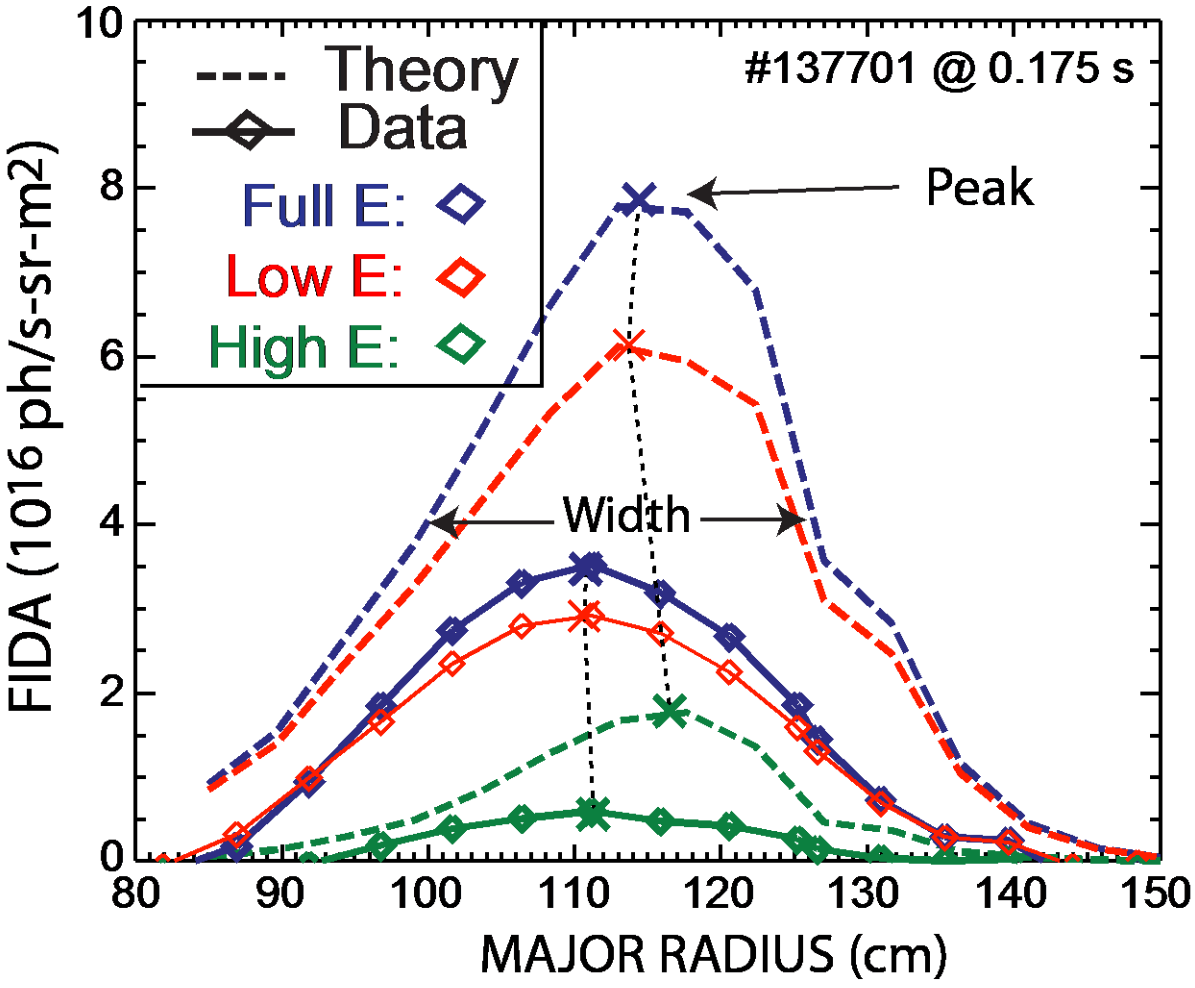

$$\chi^2_{null} = \sum_{i=1}^{N} (s_i/\sigma_i)^2/(N-1)$$

- **Compare data with "null hypothesis"**
- **Upper row has $\chi^2$ ~ 231; lower $\chi^2$ ~ 3.8**
- **Use quadratic fits to look for systematic discrepancies at low/high Doppler shift**

Theory spectra are:

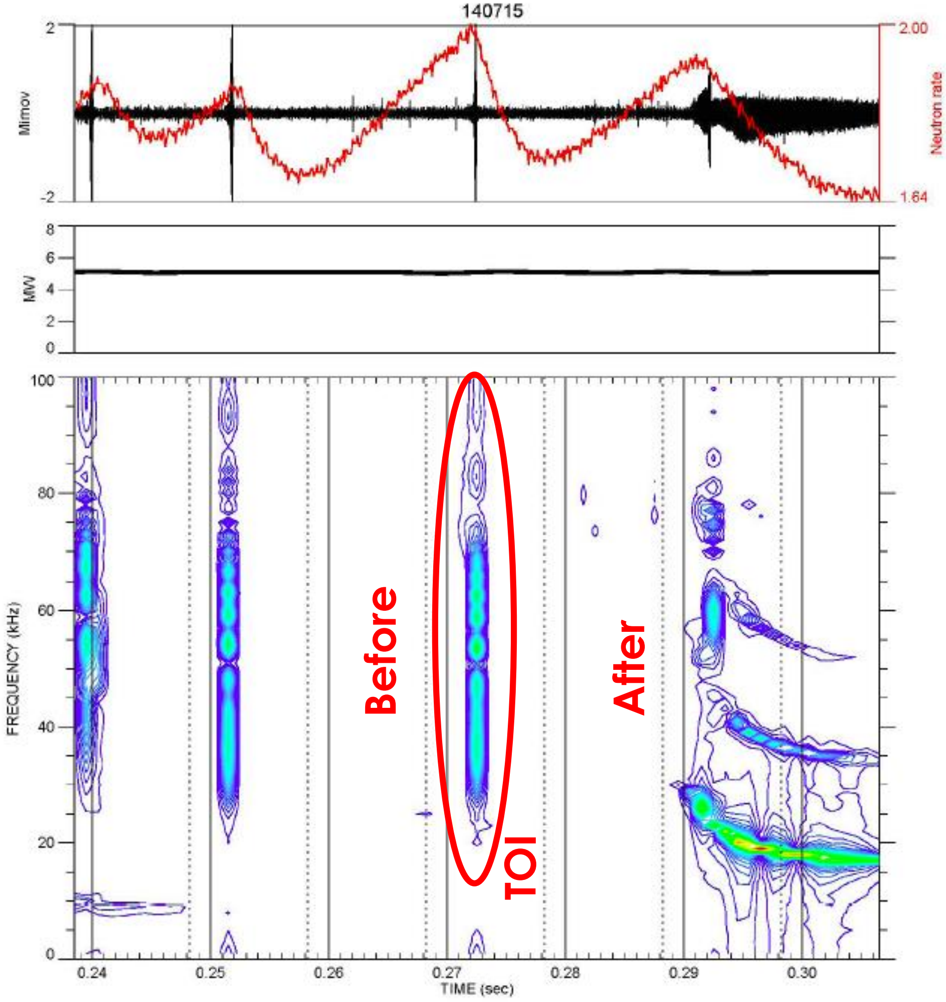
1. Smoothed with an instrument broadening function and mapped to the experimental lambda grid
2. Fitting is done over the full $E_1$ energy range, i.e. 650.5-653.8nm (dashed vertical lines)

# Compare experimental & theoretical profile shapes




- Integrate spectra over three wavelength ranges for all 16 channels
- Fit profiles to find (1) peak radiance, (2) R of peak, (3) profile width

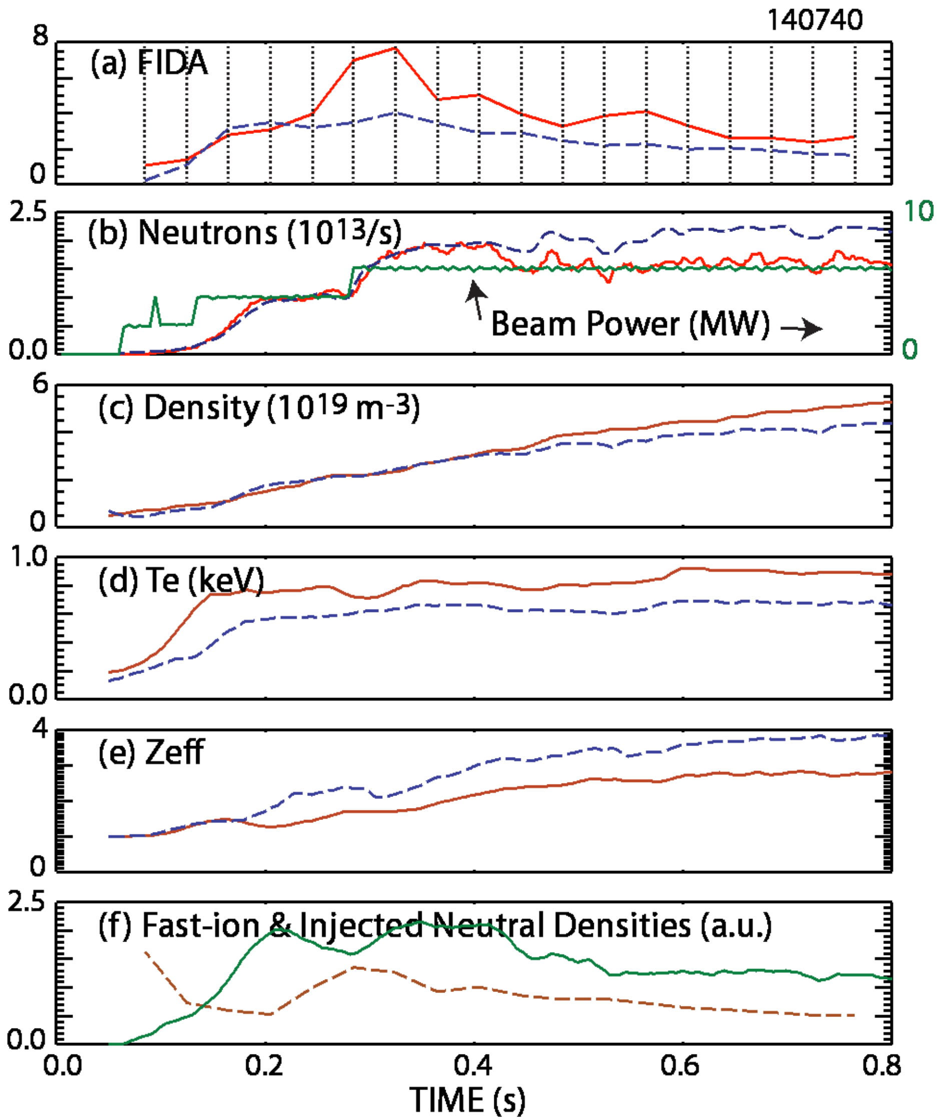
# Analyze spectra at three times (relative to the instability)




- Data acquired in 10 ms time bins
- Light blocked during readout (~1.8 ms of bin)
- Analysis times carefully selected
- Note in database whether activity is persistent, an isolated burst, etc.

# General Trends

# Time evolution of a representative shot



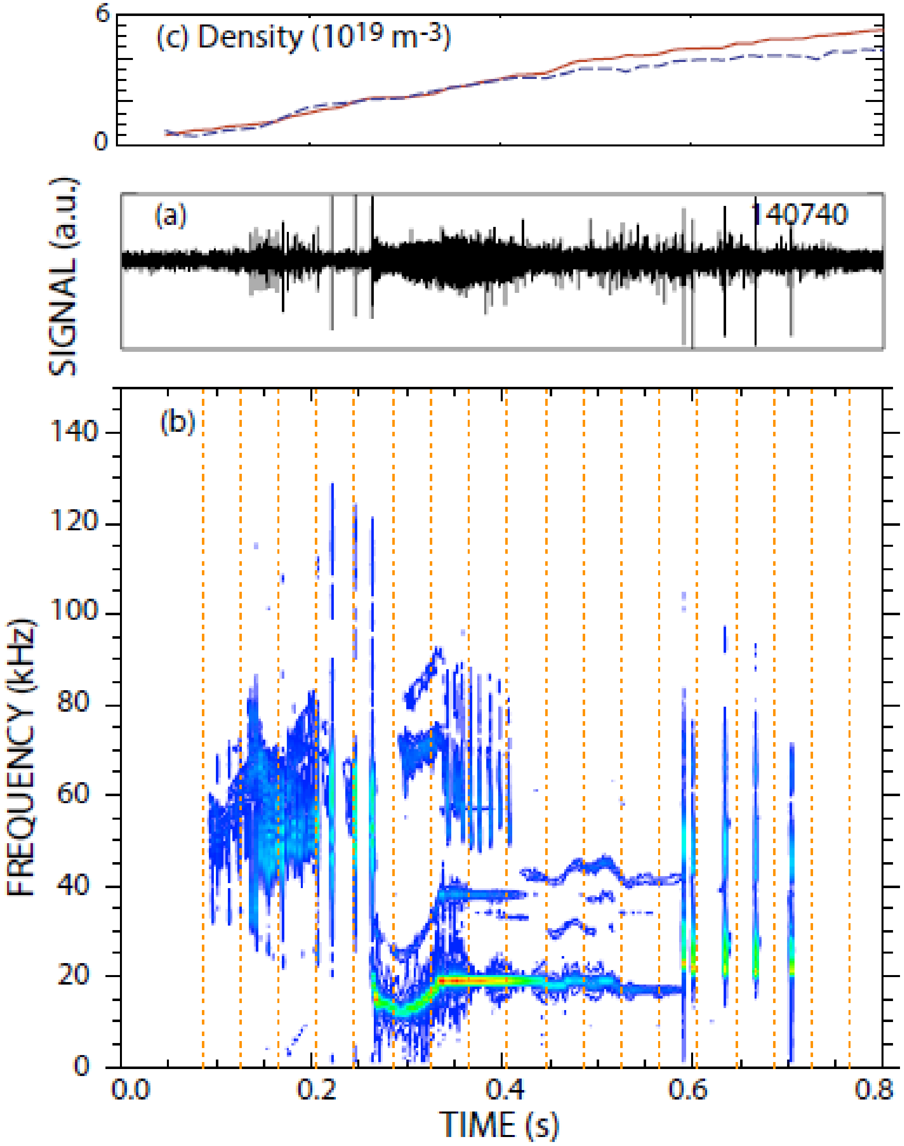

(a) Peak radiance in theory & experiment

(b) Neutrons in theory & experiment

(c-e) $n_e$, $T_e$, and $Z_{eff}$ at center (solid) and half-radius (dashed)

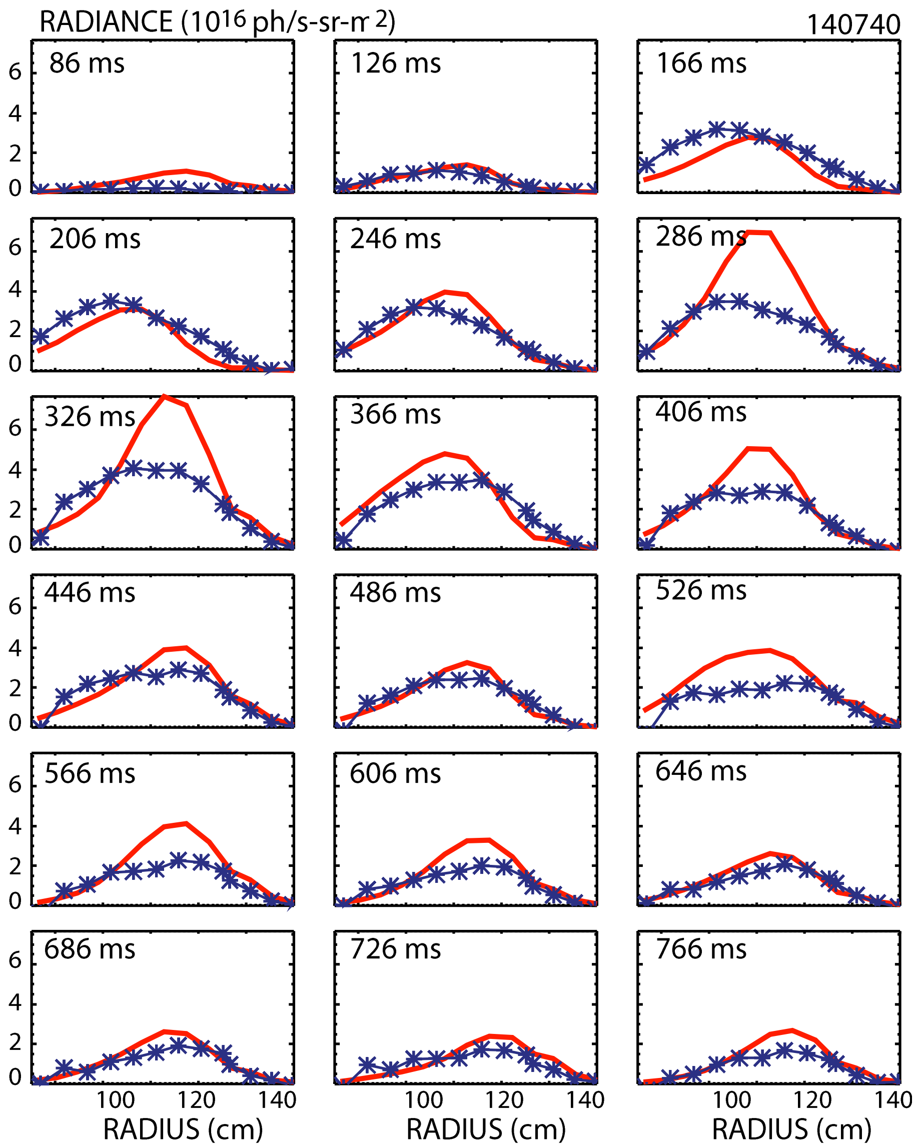
(f) Calculated fast-ion and injected-neutral densities at R=1.2 m

# MHD activity in the representative shot



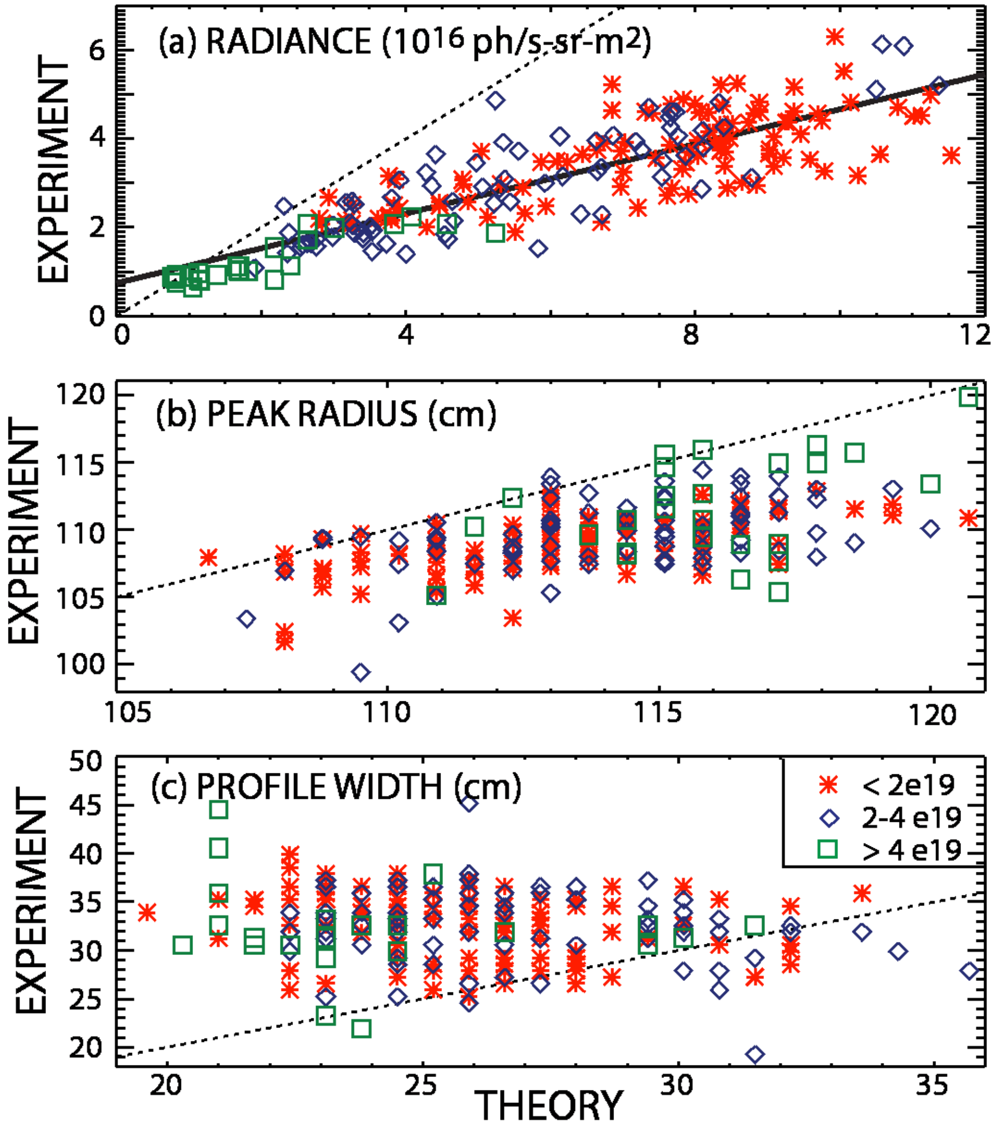

- **Wide variety of MHD but the correlation with the general trends in the FIDA data is weak**

# FIDA profiles show persistent trends throughout the shot




- Theory is usually larger than experiment
- Theory profile usually peaks at larger R than experiment
- Theory profile is usually narrower than experiment

# FIDA profiles show persistent trends throughout the database

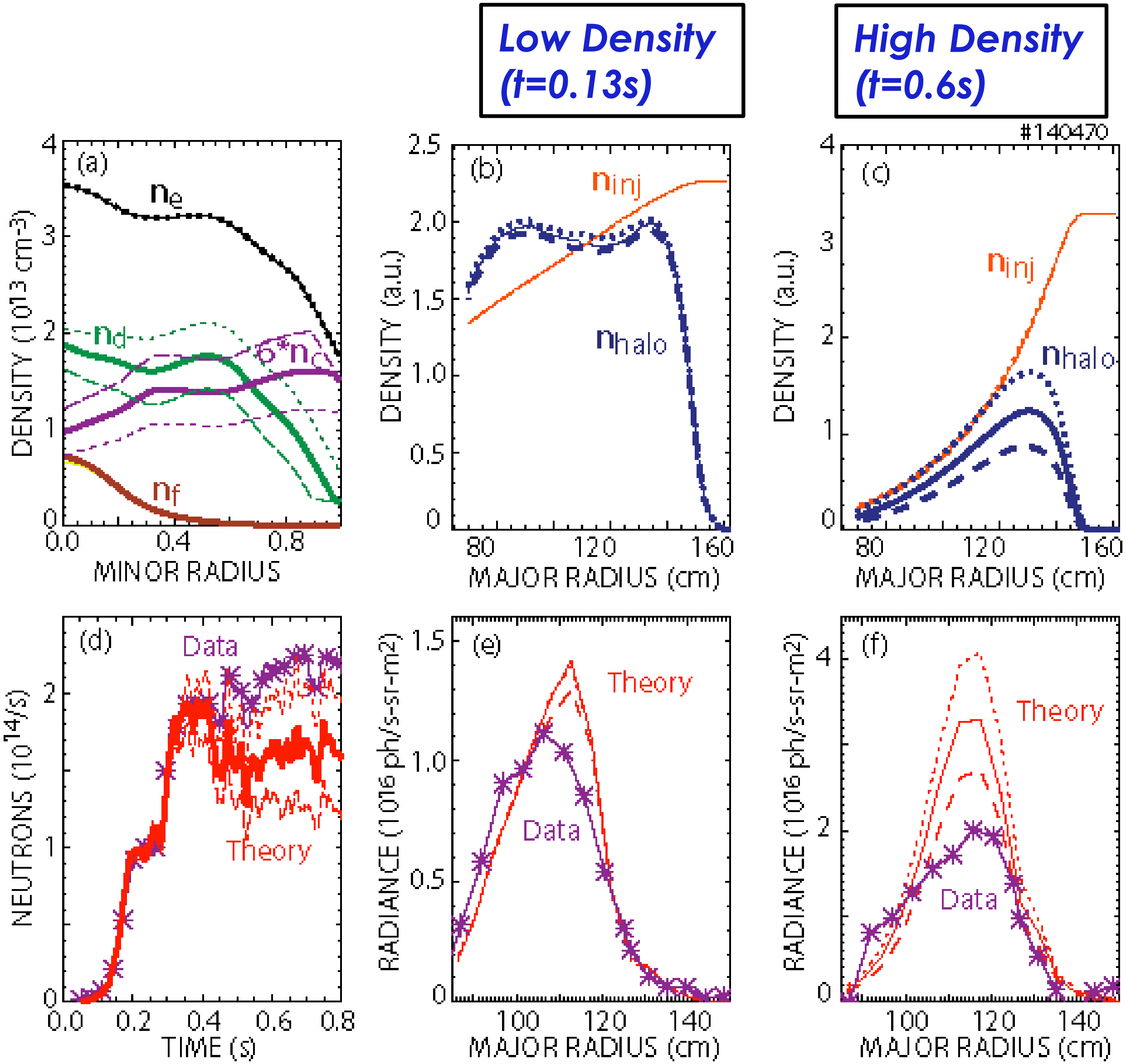



- On average, the peak radiance is 0.56 of theory but strongly correlated (r=0.86)
- Agreement best at higher $n_e$ (lower $\beta_f$, slowing-down time)
- Weak correlation with other plasma parameters
- Average peak radius is 109.7 cm in experiment but 113.8 cm in theory
- Experimental profile 26% wider than theory
- Similar results for other wavelength ranges

# What causes this discrepancy?

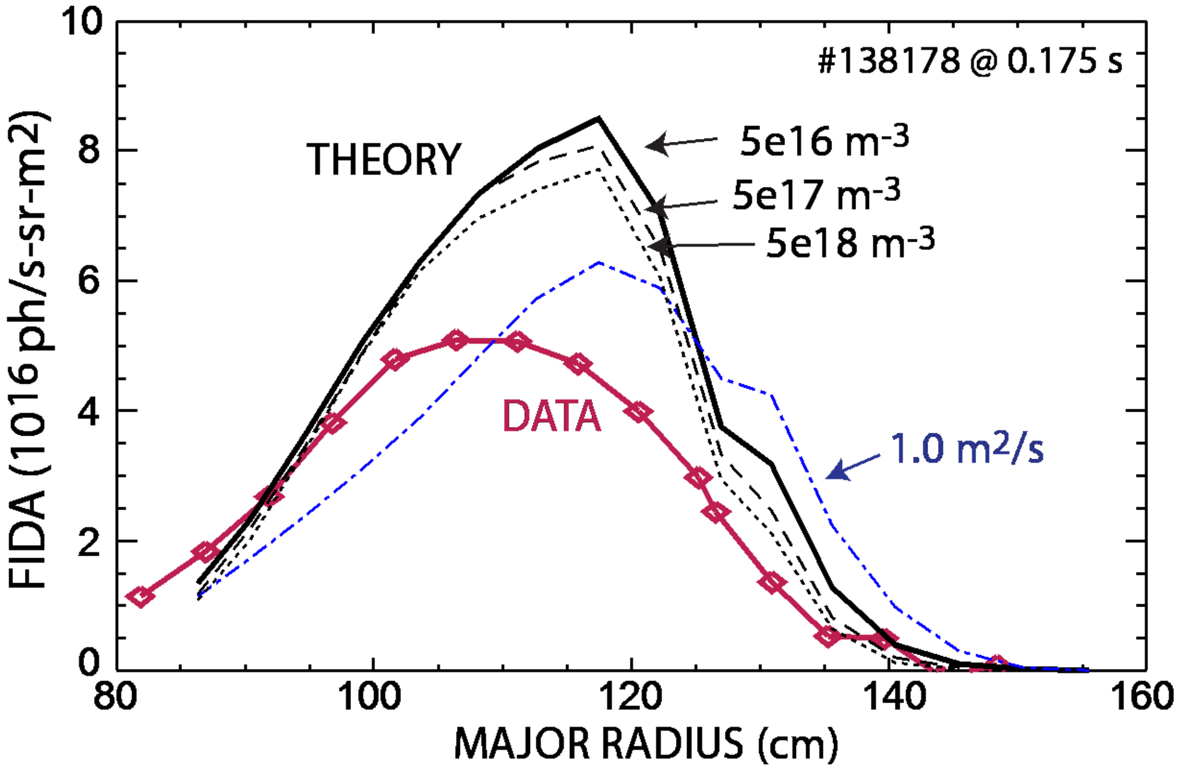
1. Procedure is flawed. No. The same procedure works well for DIII-D and ASDEX-Upgrade.
2. Experimental calibration is wrong. Unlikely. (Hard to get both magnitude & shape wrong)
3. Inputs to theory are wrong.
   (a) Beam power or $T_e$. No. (Makes neutron agreement worse.)
   (b) Density wrong. No. (Need more density to fix intensity but less to fix peak location.)
   (c) Zeff. No. (Makes neutron agreement worse.)
4. Charge exchange losses are underestimated. No.
5. Persistent MHz modes cause broadening. Unlikely. (No correlation with GAE/CAE amplitude.)
6. An unidentified process redistributes the fast ions. Probably. (Product of peak*width agrees better than either individually; better agreement at higher $n_e$ expected.)

# Flawed Zeff input cannot explain discrepancy




- **Scaled carbon density up & down 25%**
- **Alters predictions but not enough**
- **Also increases discrepancy with neutrons**

# Edge charge-exchange losses cannot explain discrepancy



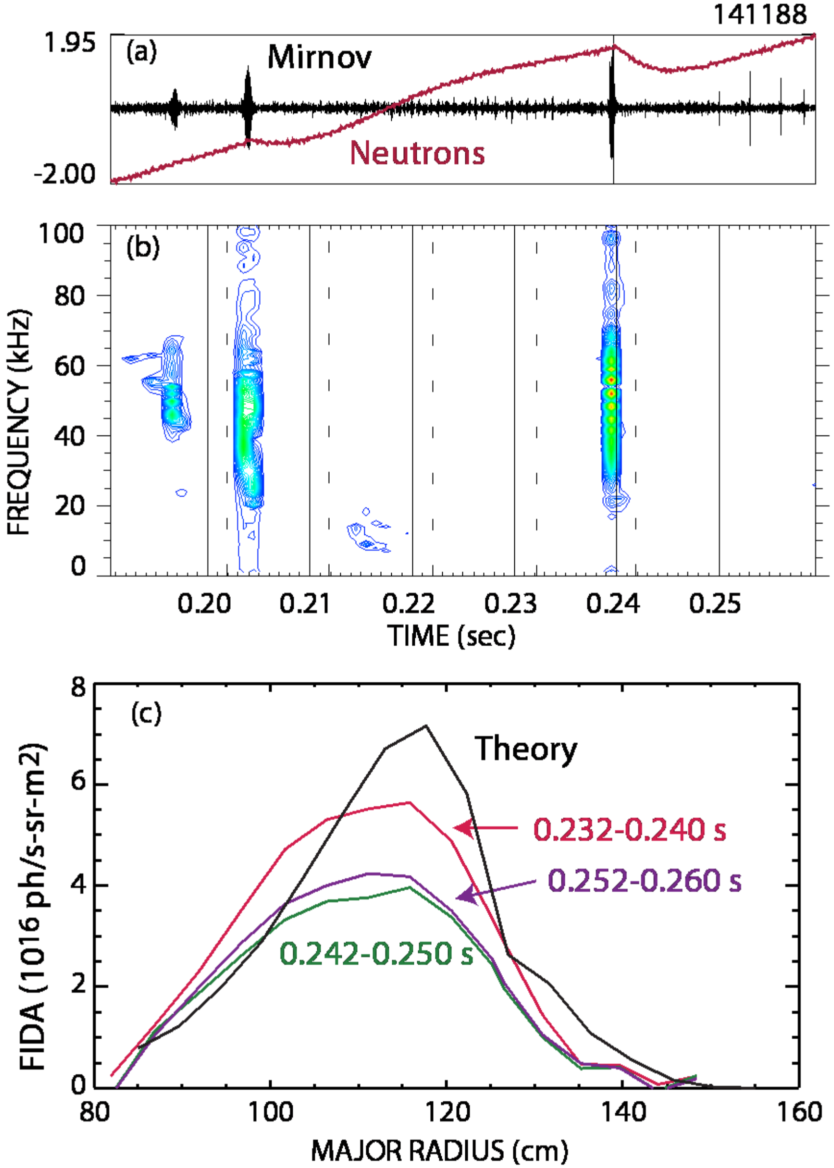

- Increased edge neutral density two orders of magnitude over baseline
- Small change in predicted profile

# What could this unidentified process be?

- A persistent mode undetected by magnetics
- Fast-ion transport by electromagnetic microturbulence
- Error field

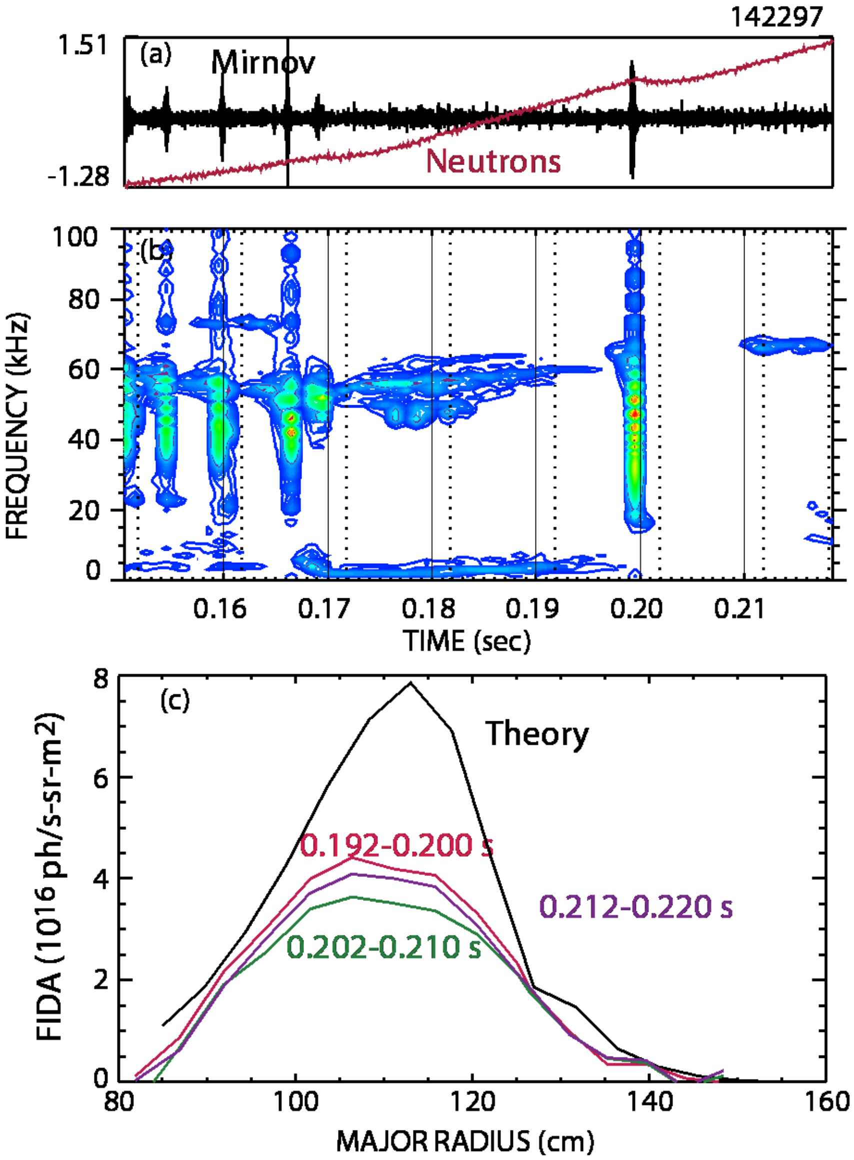
# Effects of ALE, TAE avalanche, EPM, and steady TAEs

# Every ALE causes profile flattening



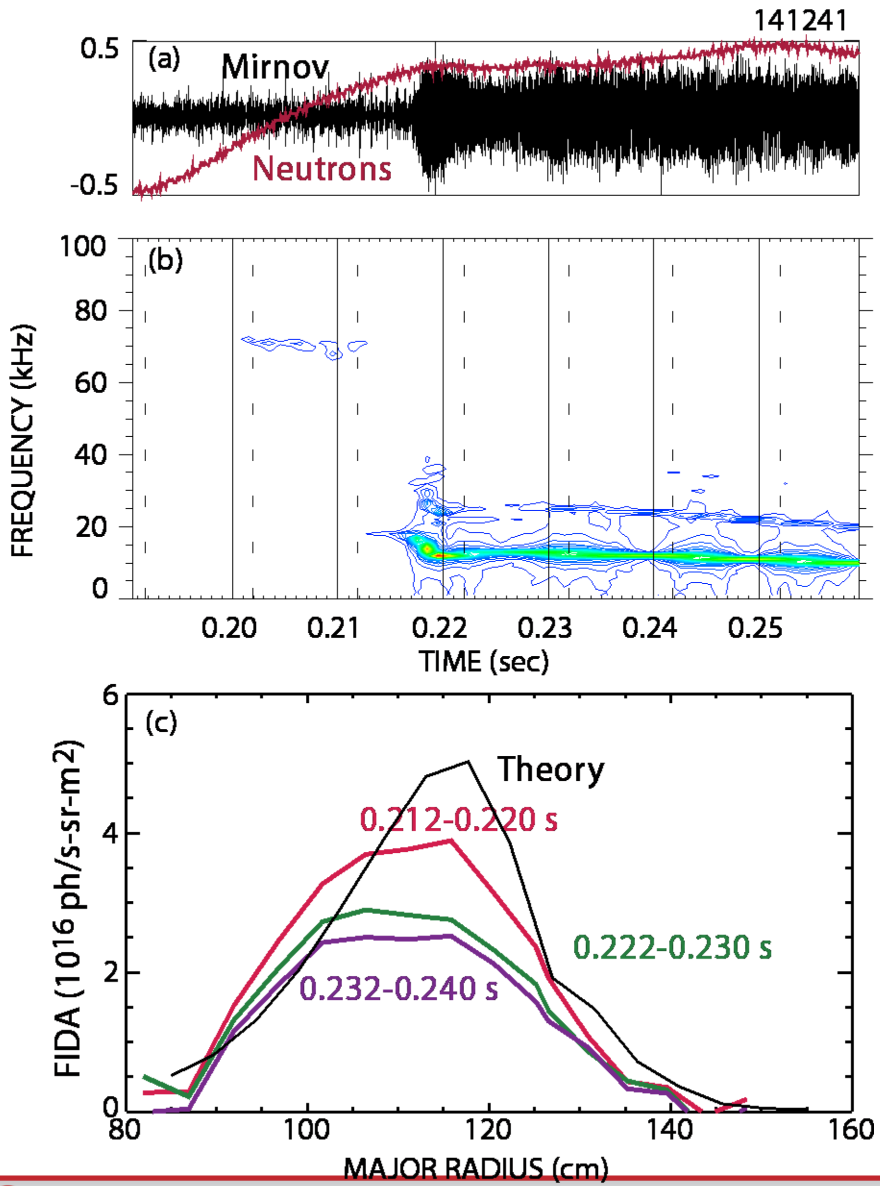

- **Profile immediately after the burst is $0.81 \pm 0.06$ of prior profile.**
- **No systematic change in spectral shape**
- **Consistent with JT-60U neutron profile measurements and modeling**

# TAE avalanches usually cause profile flattening



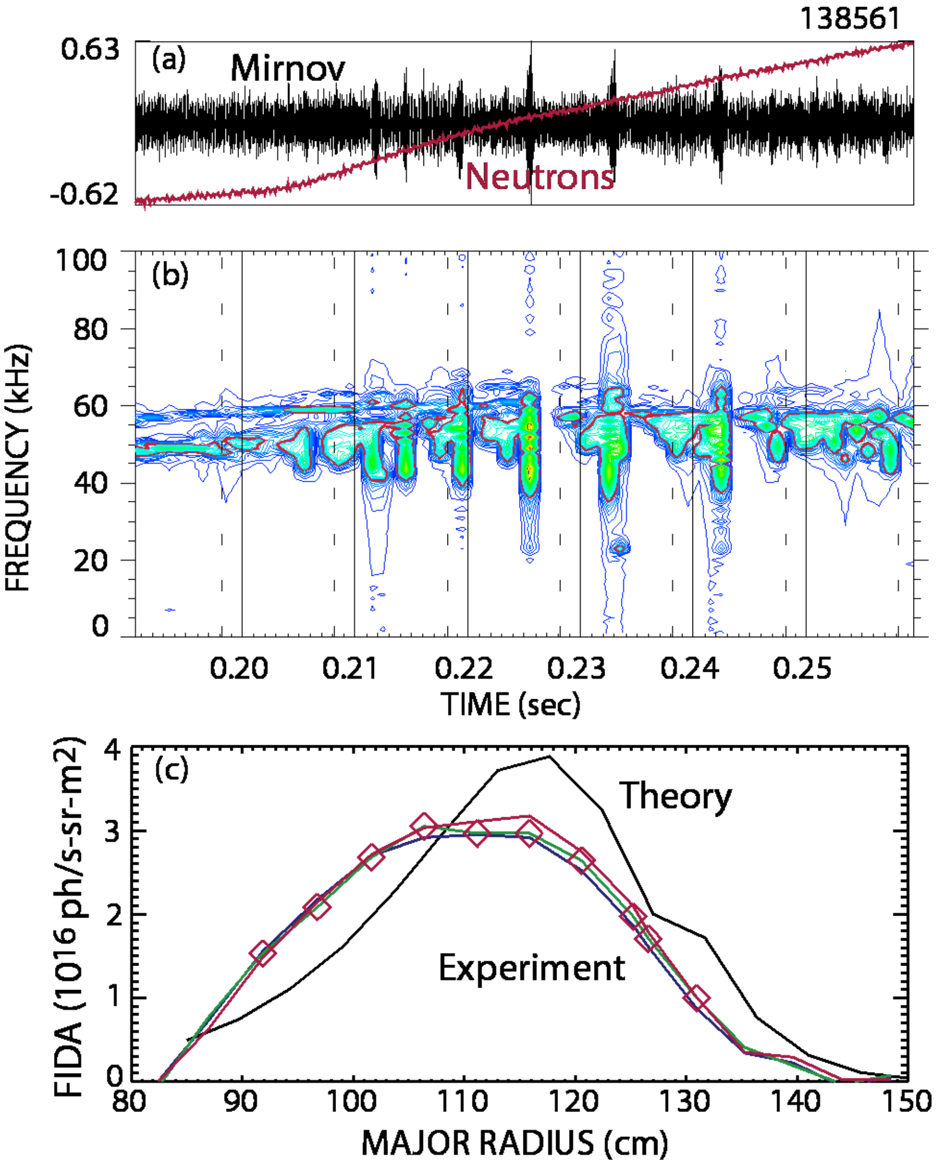

- Nearly all cases show flattening
- No systematic change in spectral shape
- Consistent with Darrow's conclusion that losses are broadly distributed in phase space

# EPMs cause profile flattening




- **Flattened profile persists in subsequent time slices**
- **No systematic change in spectral shape**

# TAEs are too rapid to detect effect of individual events




- **As expected, successive time bins are virtually identical**
- **Agreement good at small major radius but poor at large major radius**
- **No systematic change in spectral shape**

# Conclusions & Outlook

- The experimental radial profile has smaller radiance, is wider, and peaks at smaller major radius than theory predicts.
- An unidentified persistent fast-ion transport mechanism is the most likely explanation.
- ALEs, TAE avalanches, and EPMs flatten the FIDA profile without appreciably altering the spectral shape.

**We'll investigate all of these issues with better profile diagnostics in NSTX-U!**