Analysis of Fast-ion D$_\alpha$ Data from NSTX

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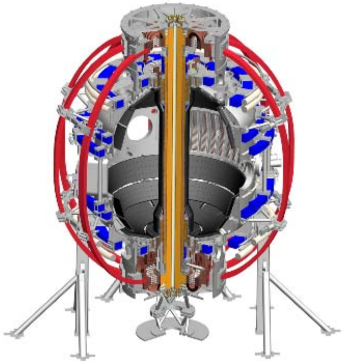


INTRODUCTION

- **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:**

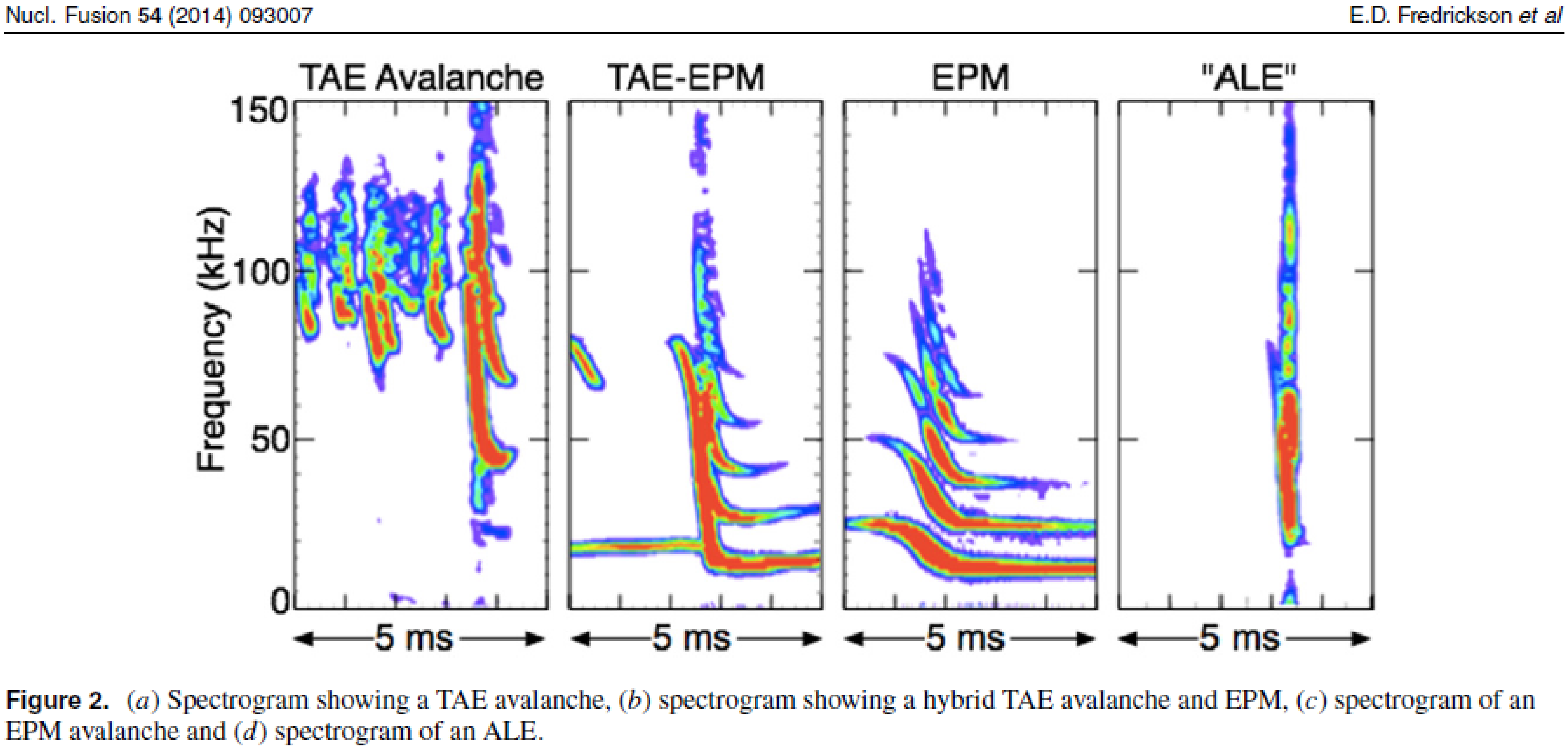
$\langle\beta_{fast}\rangle / \langle\beta_{total}\rangle$ V_{fast} / V_A $\delta S/S$ $\delta B/B$

- **We extend this database with data from the vertical Fast Ion D_α (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

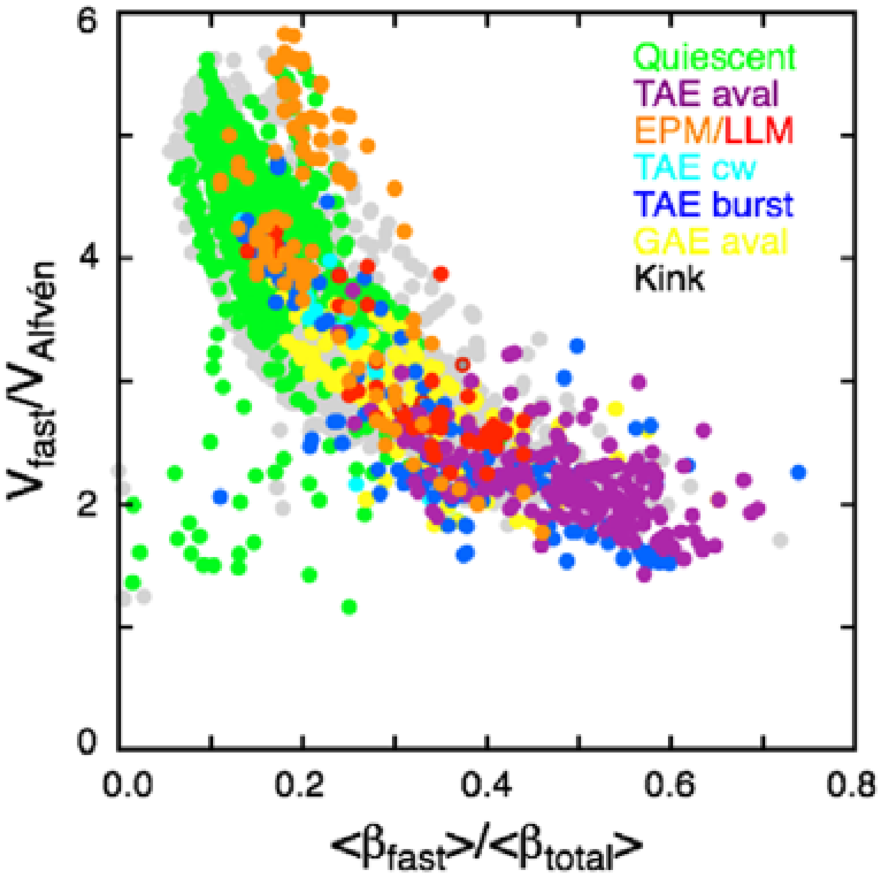
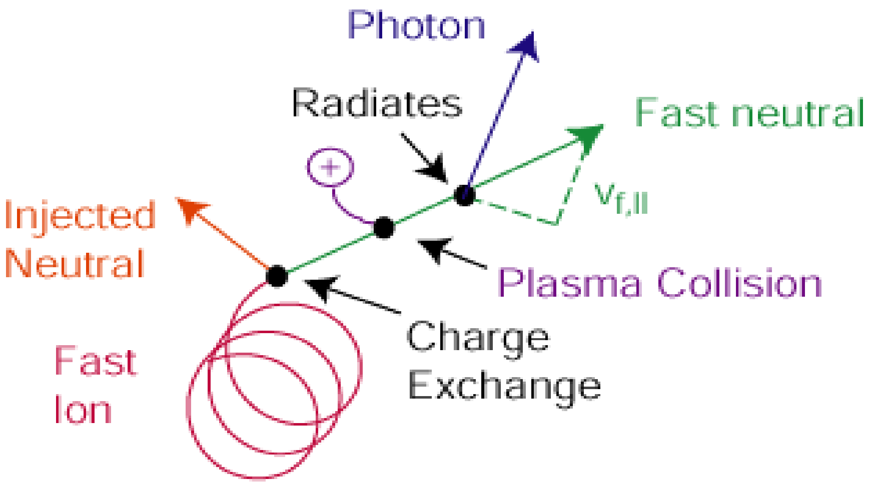


Figure 3. Existence plot for a variety of MHD activities.

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

- **Avalanches & ALEs require large β_{fast}**
- **Quiescent conditions at higher n_e**

FIDA is an application of Charge Exchange Recombination Spectroscopy

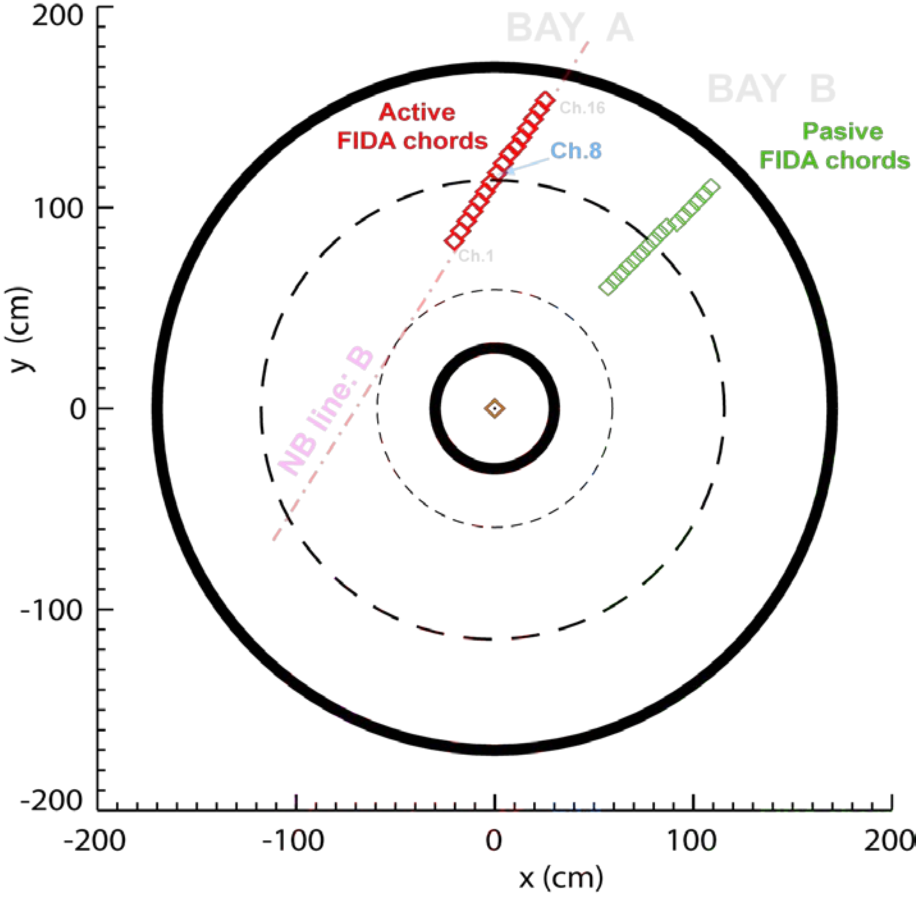


W. Heidbrink, Rev. Sci. Instrum. **81** (2010) 10D727

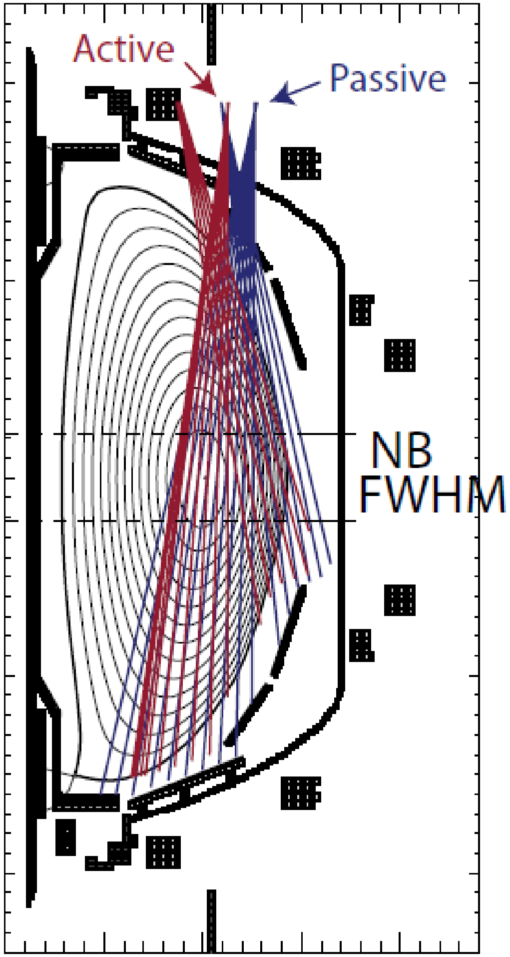
1. **The fast ion exchanges an electron with an injected neutral**
2. **Neutrals in the n=3 state relax to an equilibrium population; some radiate**
3. **The Doppler shift of the emitted photon depends on a component of the fast-ion velocity**

Vertical FIDA data were routinely archived in 2010

Plan view

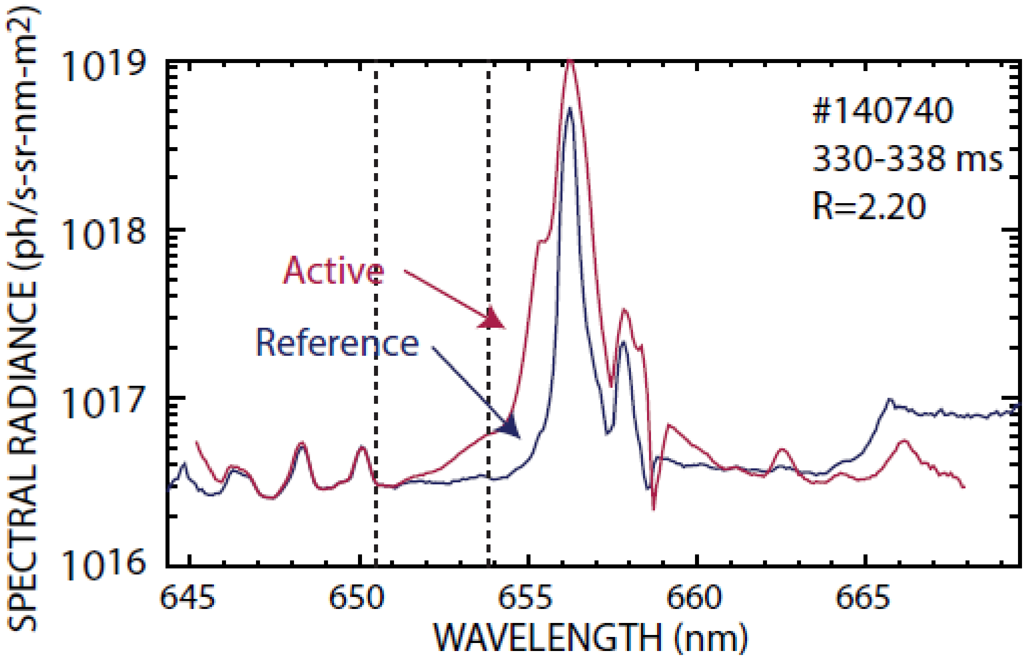


Elevation



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

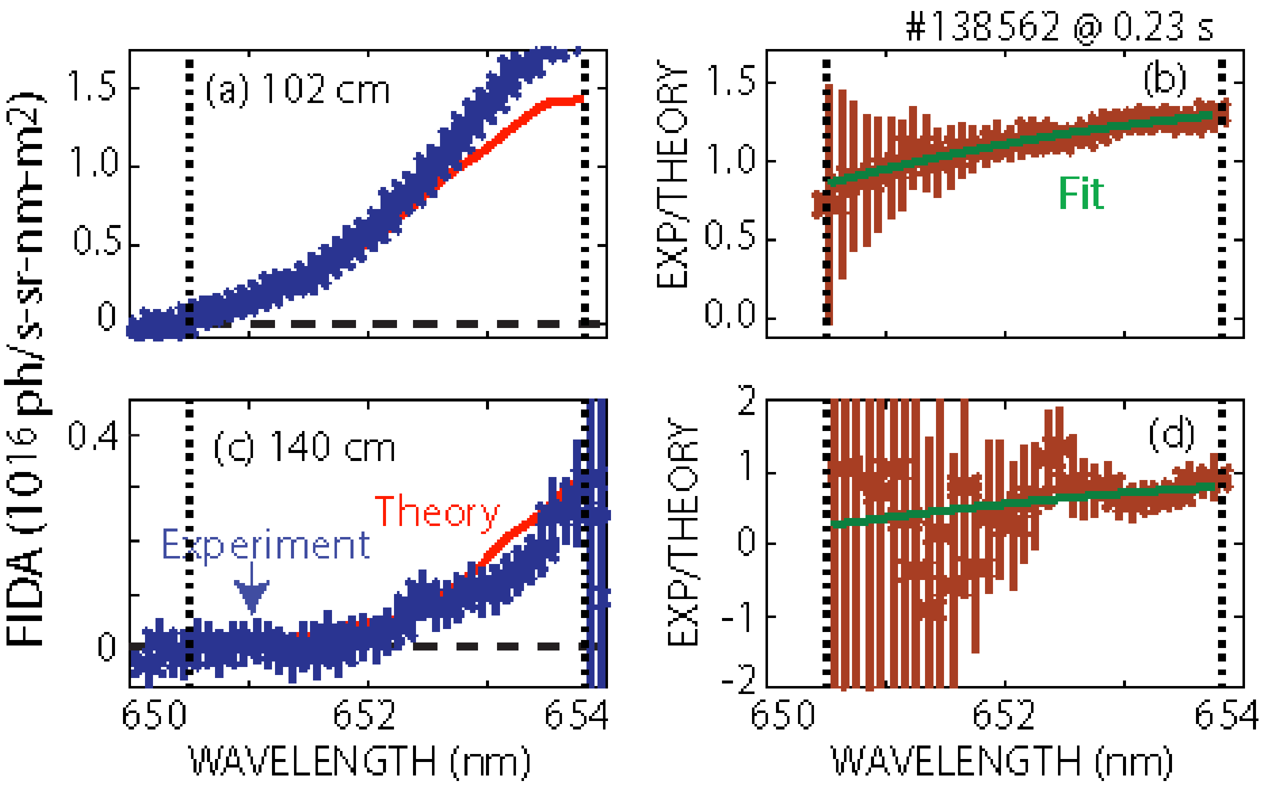
Use NUBEAM & FIDASIM to predict the signal

- **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, λ=650.5-653.8nm
  - Low energy range E_2: 11.5-31.3 keV, λ=652.3-653.8nm
  - High energy range E_3: 31.3-68.0 keV, λ=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



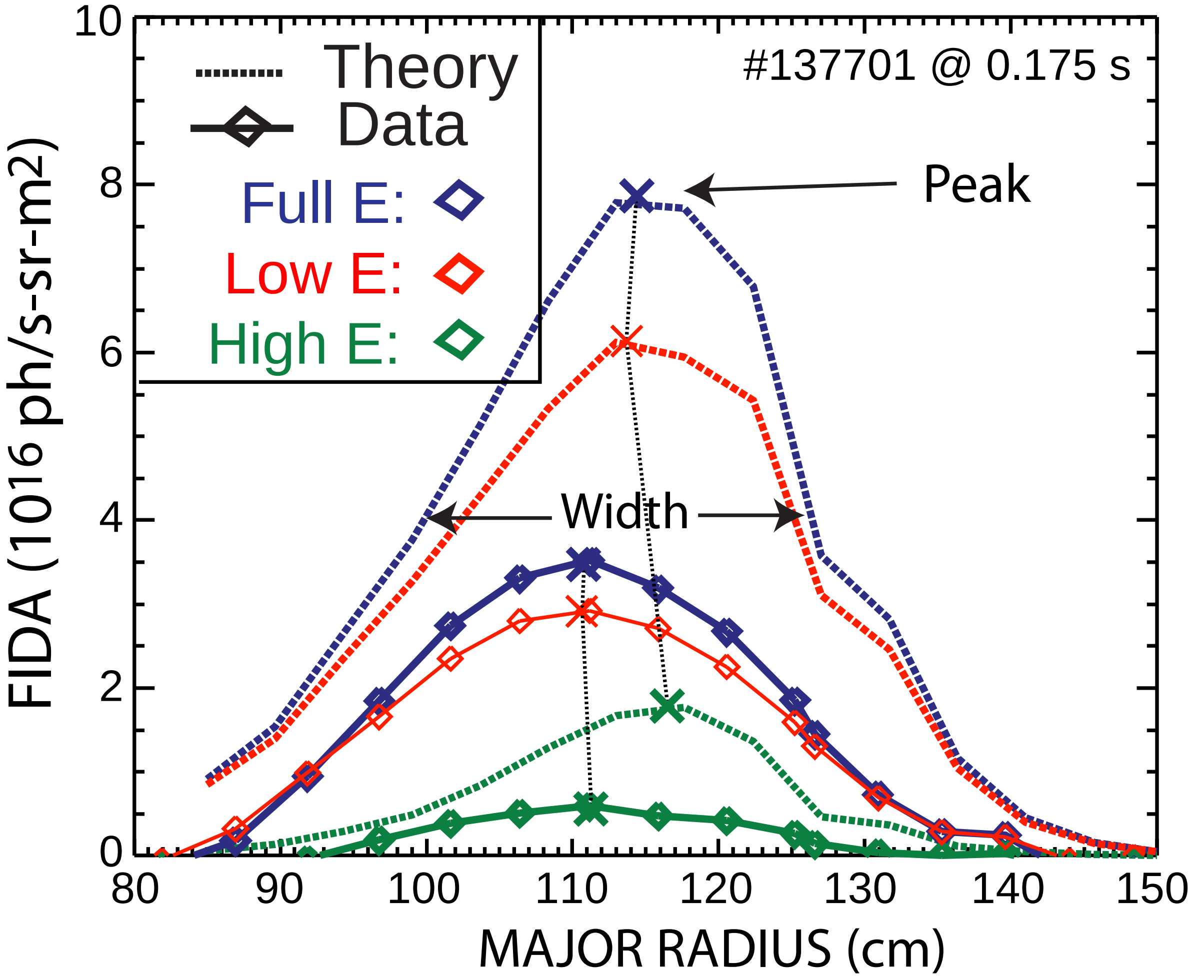
$$\chi^2_{null} = \sum_{i=1}^{N} (s_i/\sigma_i)^2/(N-1)$$

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

Theory spectra are:

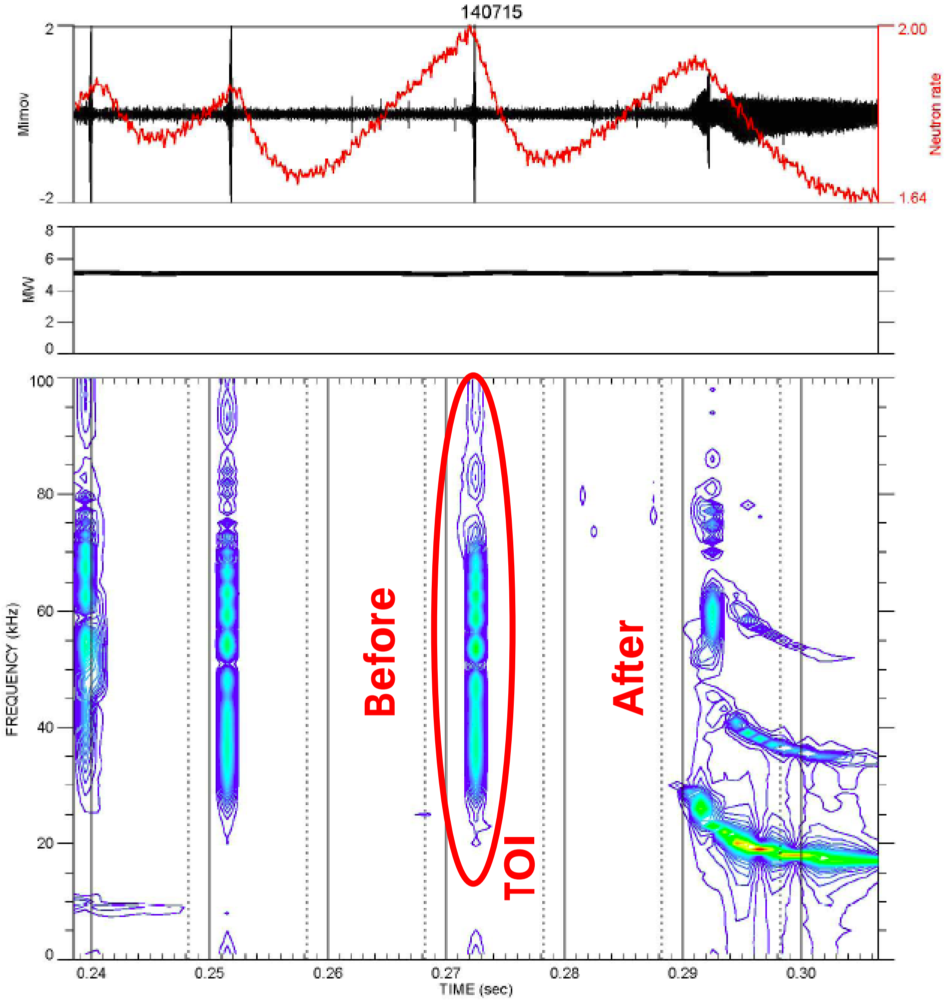
1. Smoothed with an instrument broadening function and mapped to the experimental lambda grid
2. Fitting is done over the full E_1 energy range, i.e. 650.5-653.8nm (dashed vertical lines)

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**

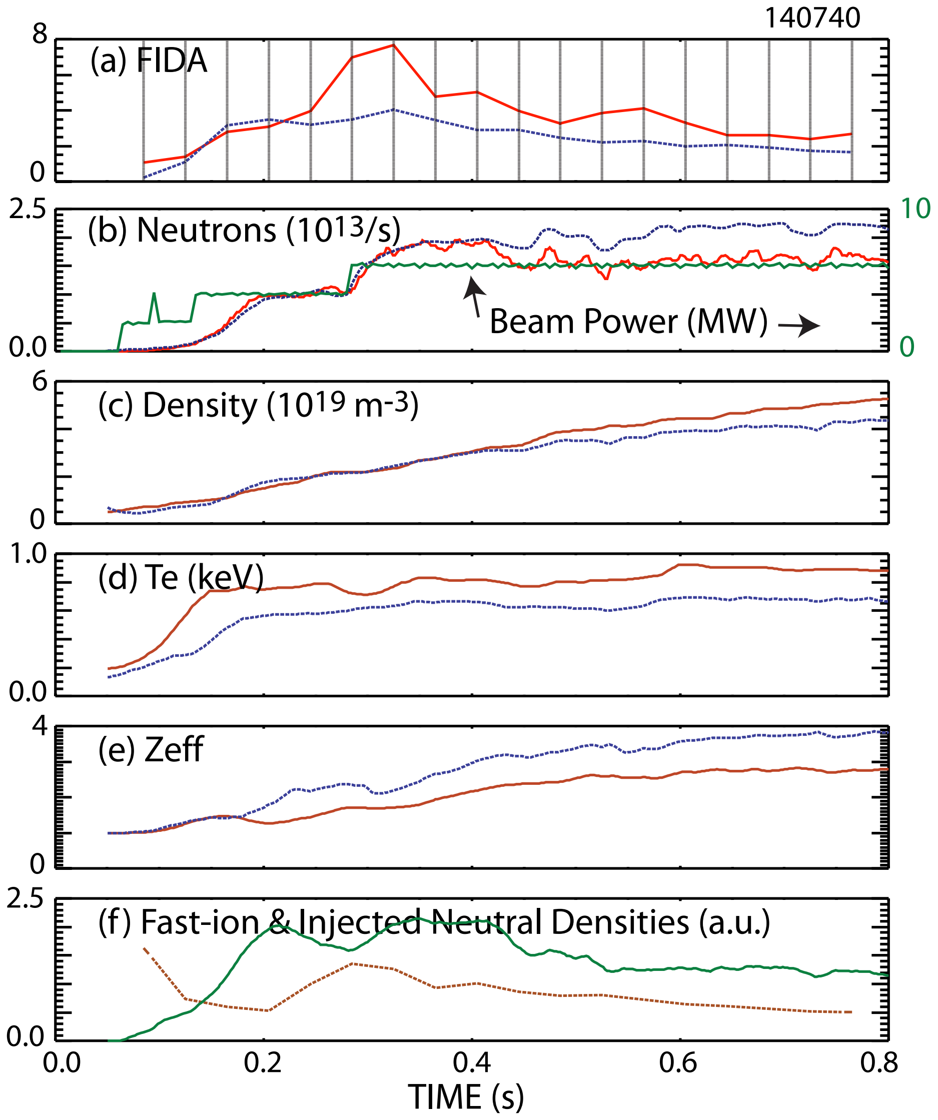
Analyze spectra at three times (relative to the instability)



- **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



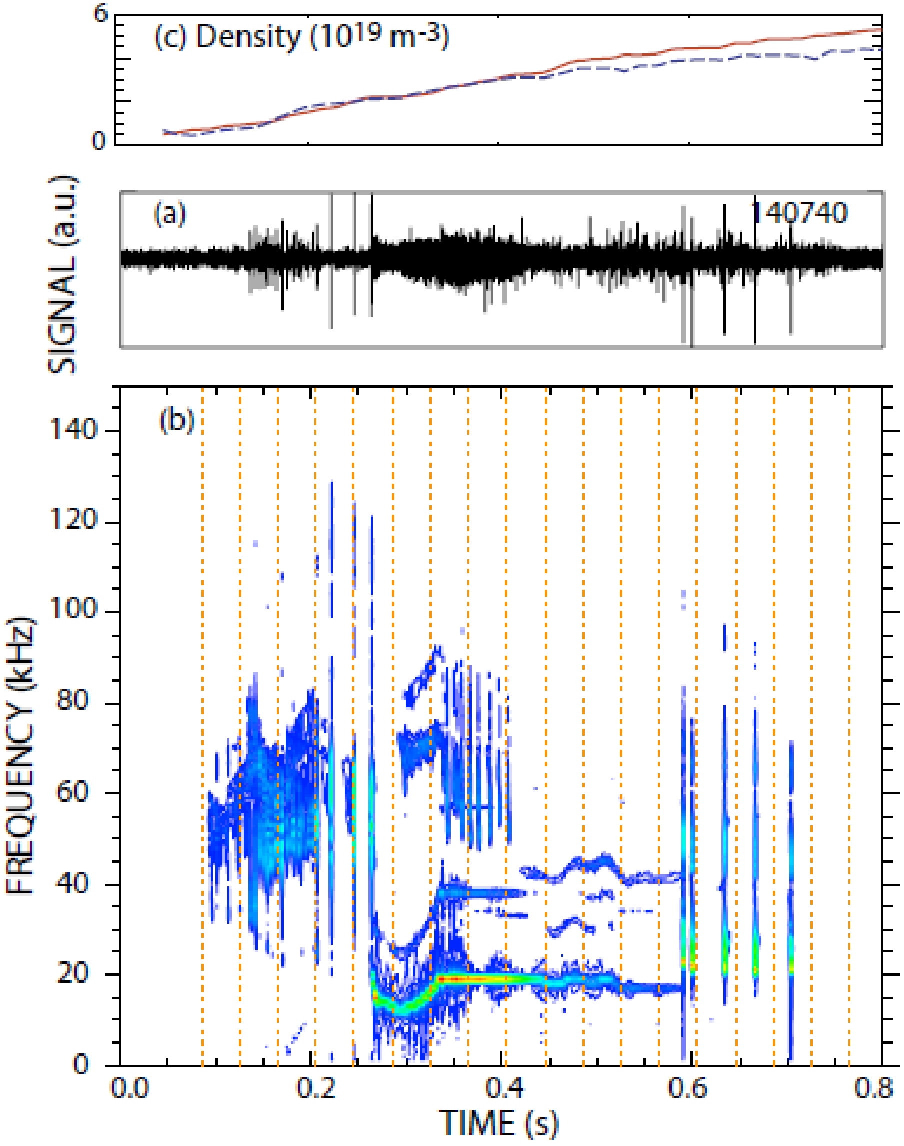
(a) Peak radiance in theory & experiment

(b) Neutrons in theory & experiment

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

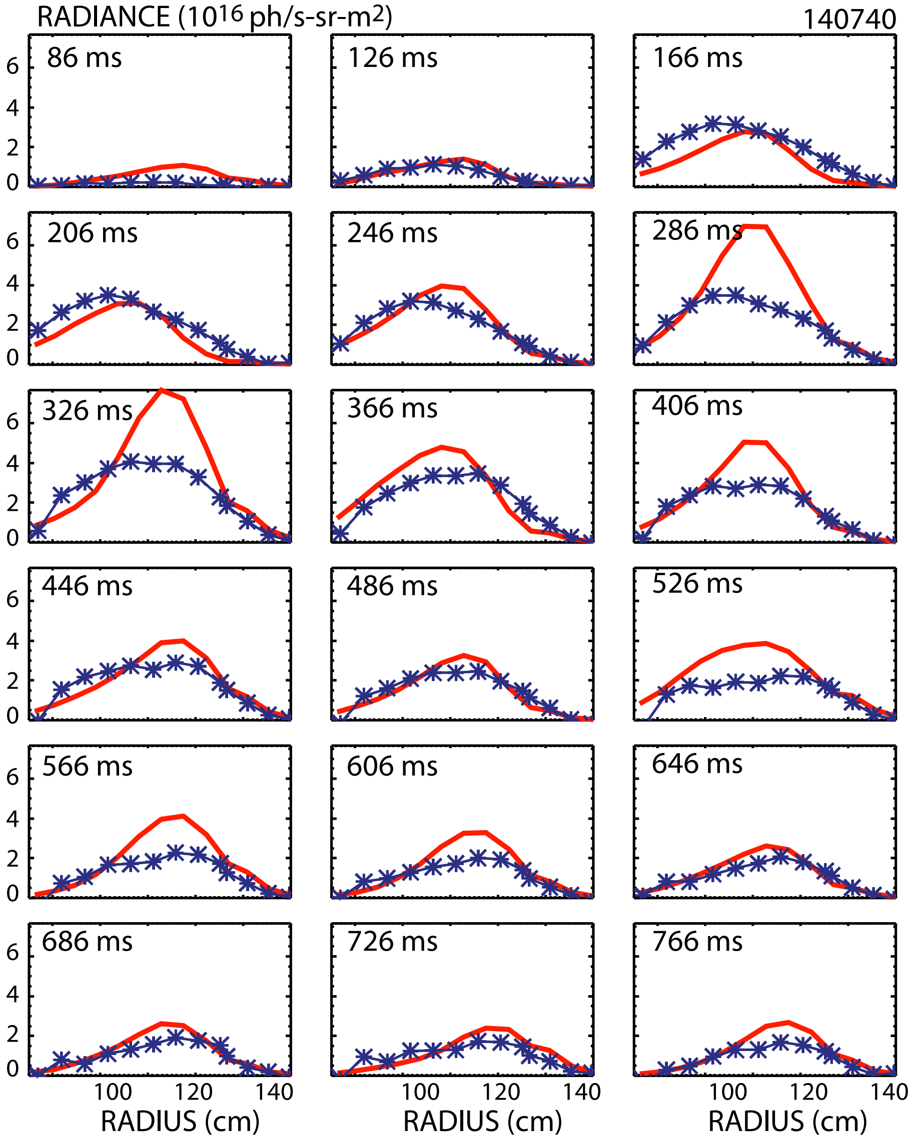
(f) Calculated fast-ion and injected-neutral densities at R=1.2 m

MHD activity in the representative shot



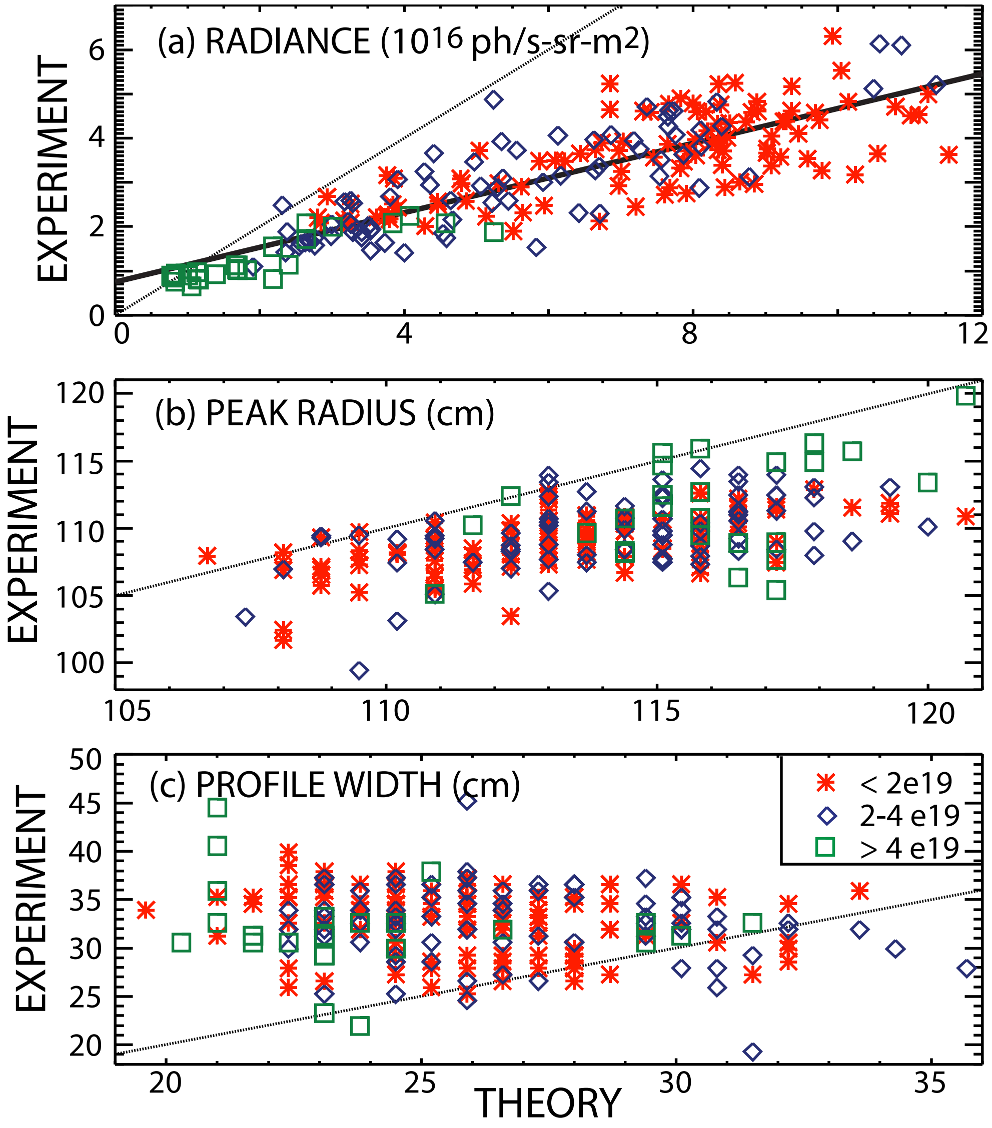
- **Wide variety of MHD but the correlation with the general trends in the FIDA data is weak**

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 β_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.)

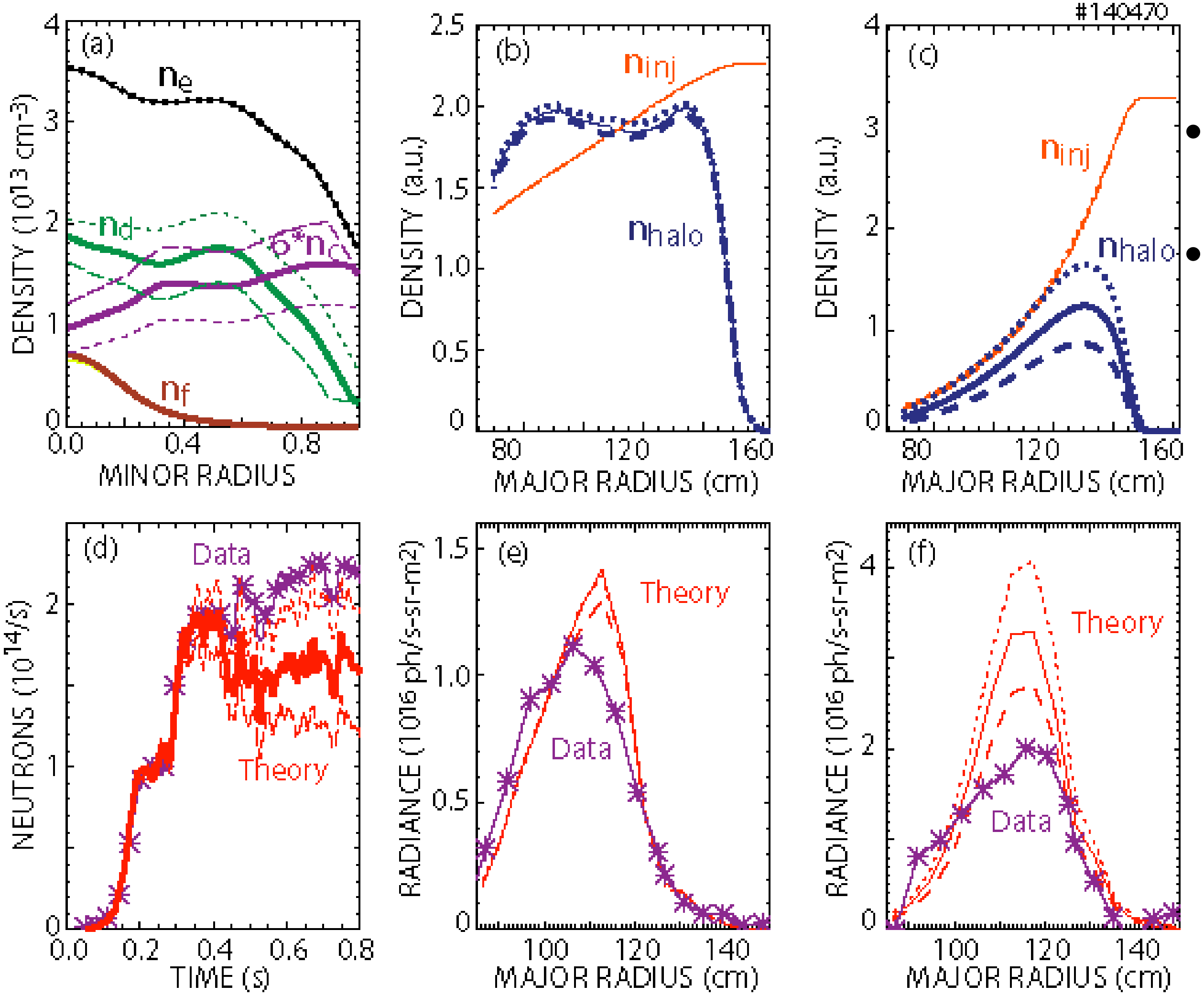
   (b) Density wrong. No. (Need more density to fix intensity but less to fix peak location.)

   (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

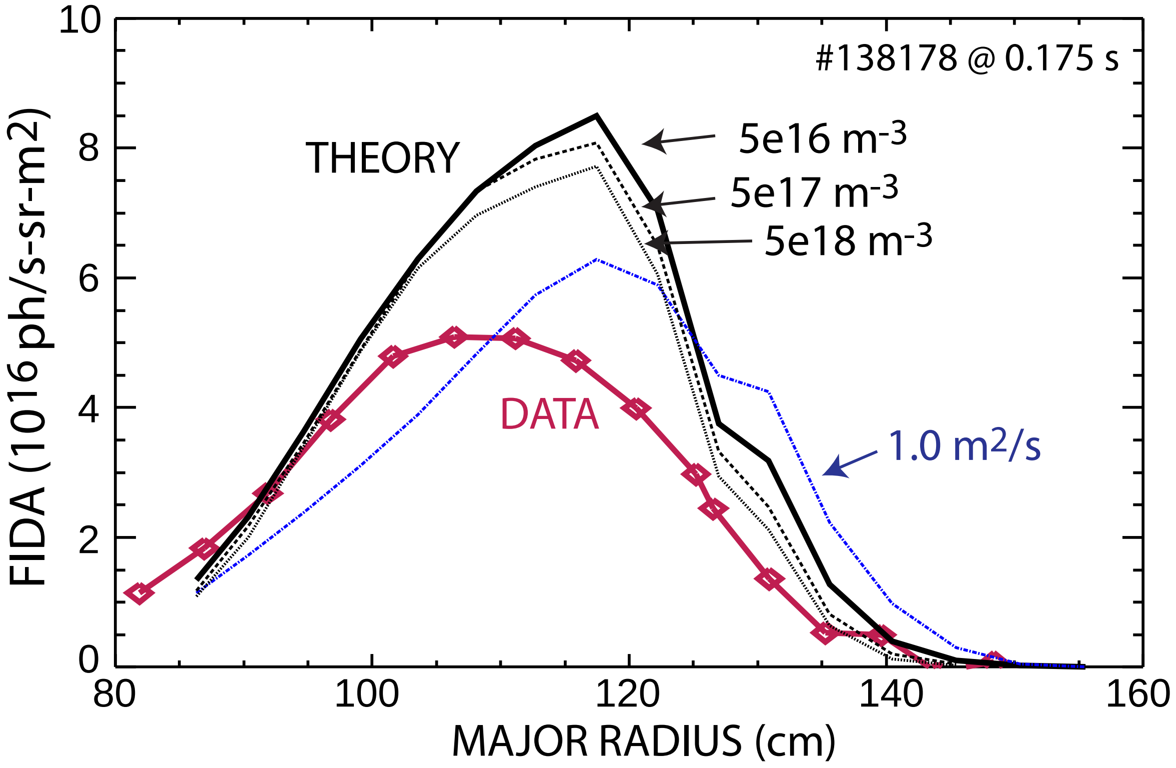
Low Density (t=0.13s)

High Density (t=0.6s)



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

Edge charge-exchange losses cannot explain discrepancy



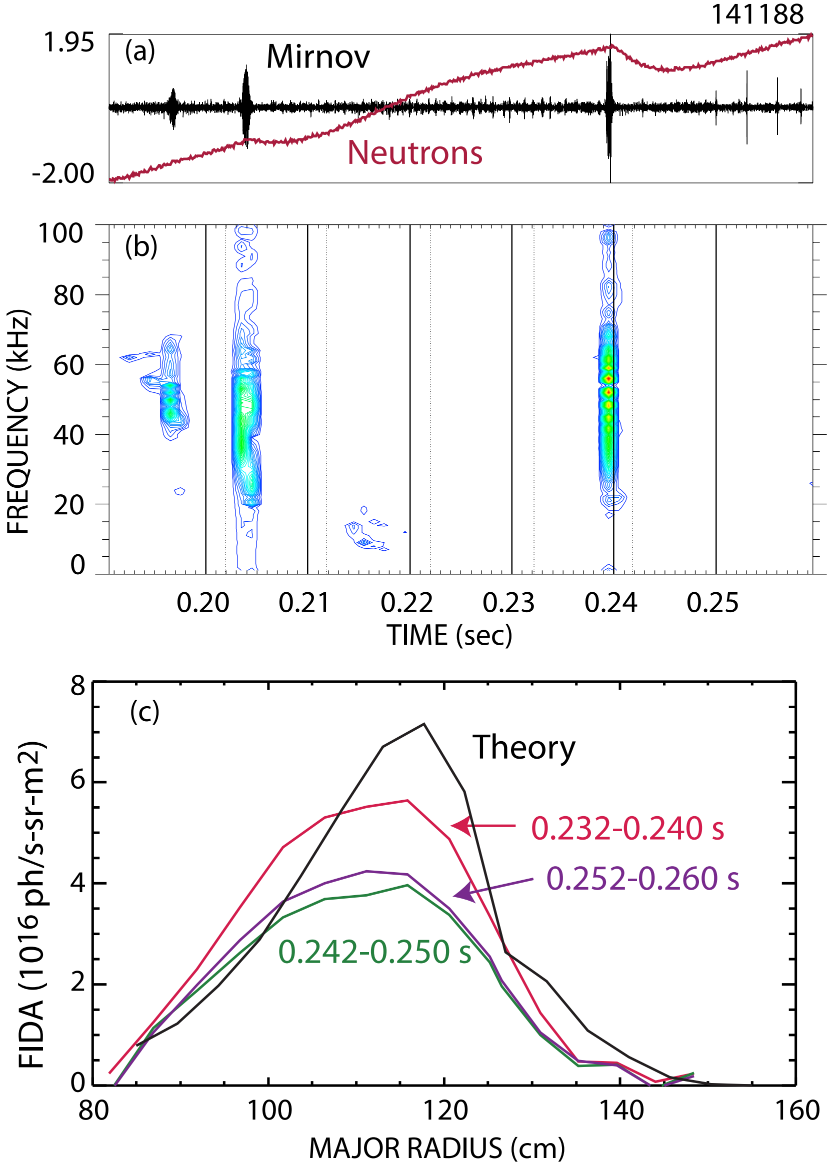
- **Increased edge neutral density two orders of magnitude over baseline**
- **Small change in predicted profile**

What could this unidentified process be?

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

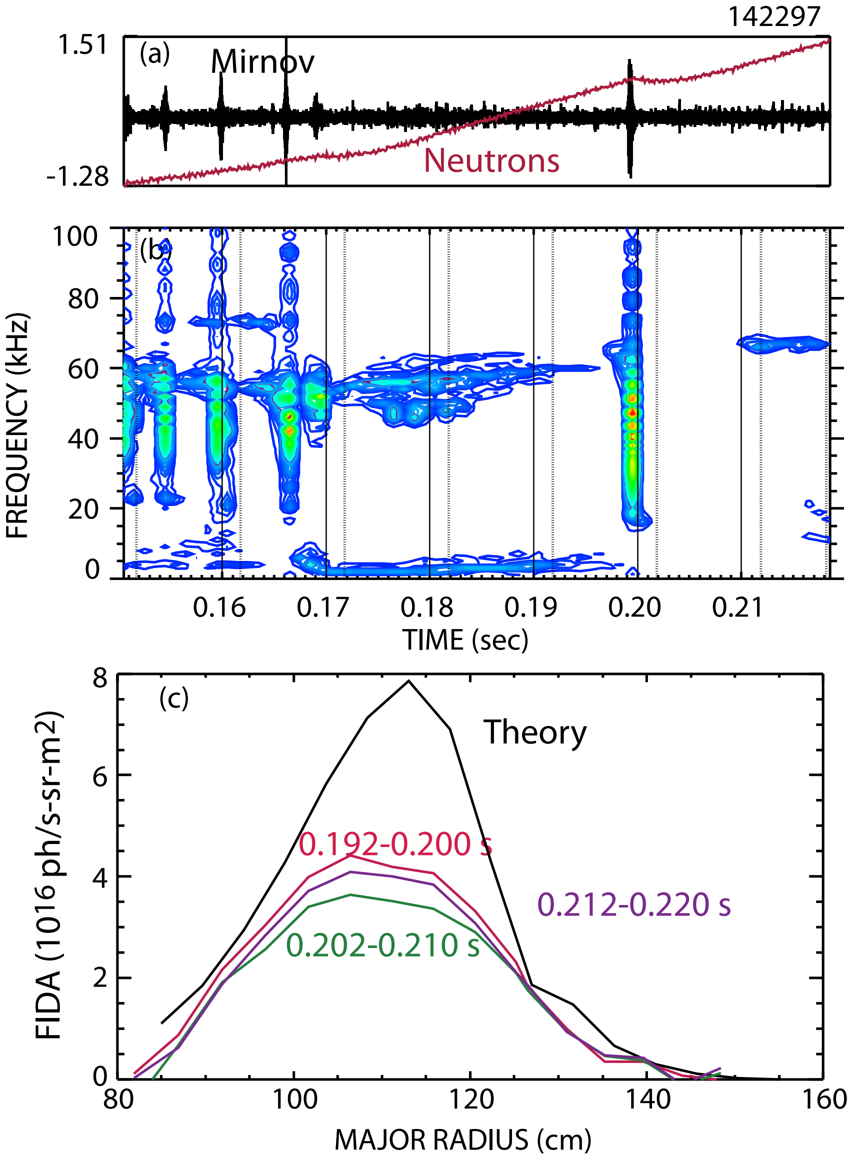
Effects of ALE, TAE avalanche, EPM, and steady TAEs

Every ALE causes profile flattening



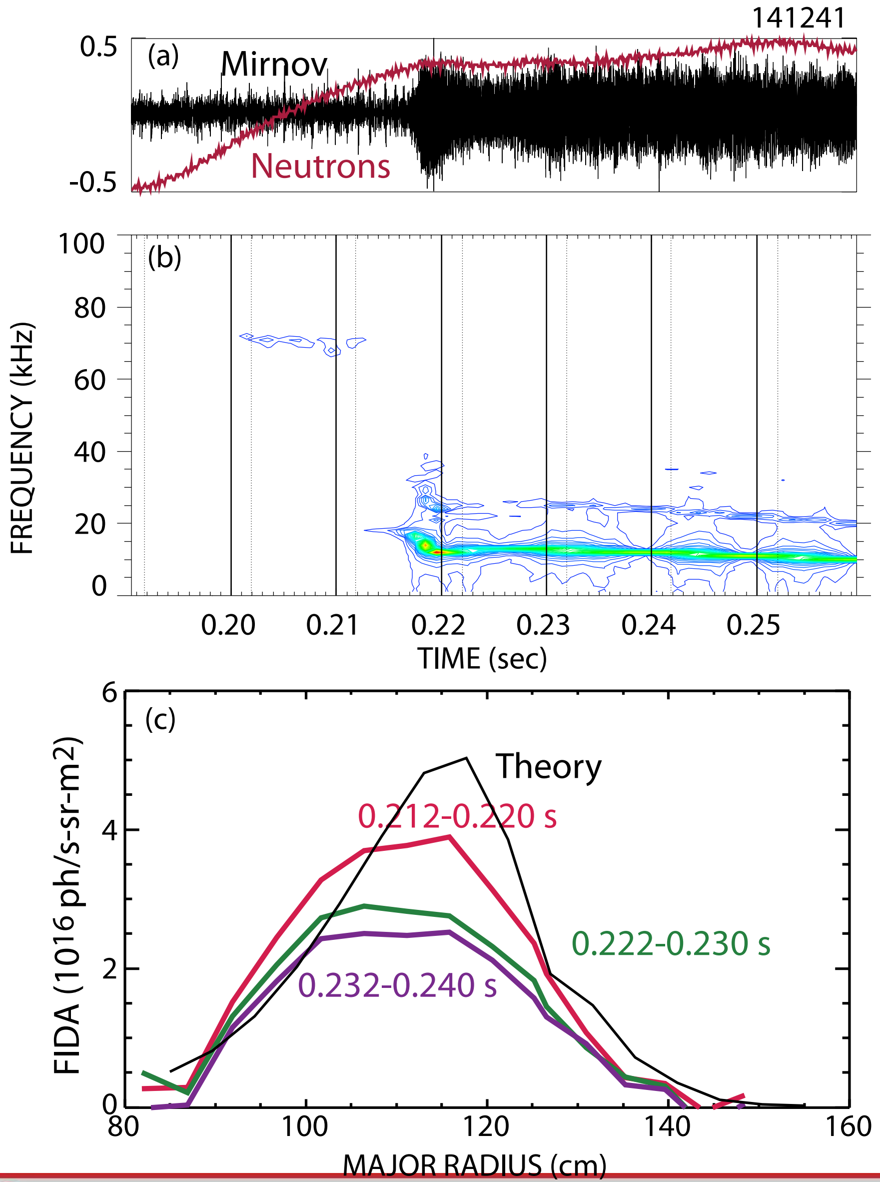
- **Profile immediately after the burst is 0.81 ± 0.06 of prior profile.**
- **No systematic change in spectral shape**
- **Consistent with JT-60U neutron profile measurements and modeling**

TAE avalanches usually cause profile flattening



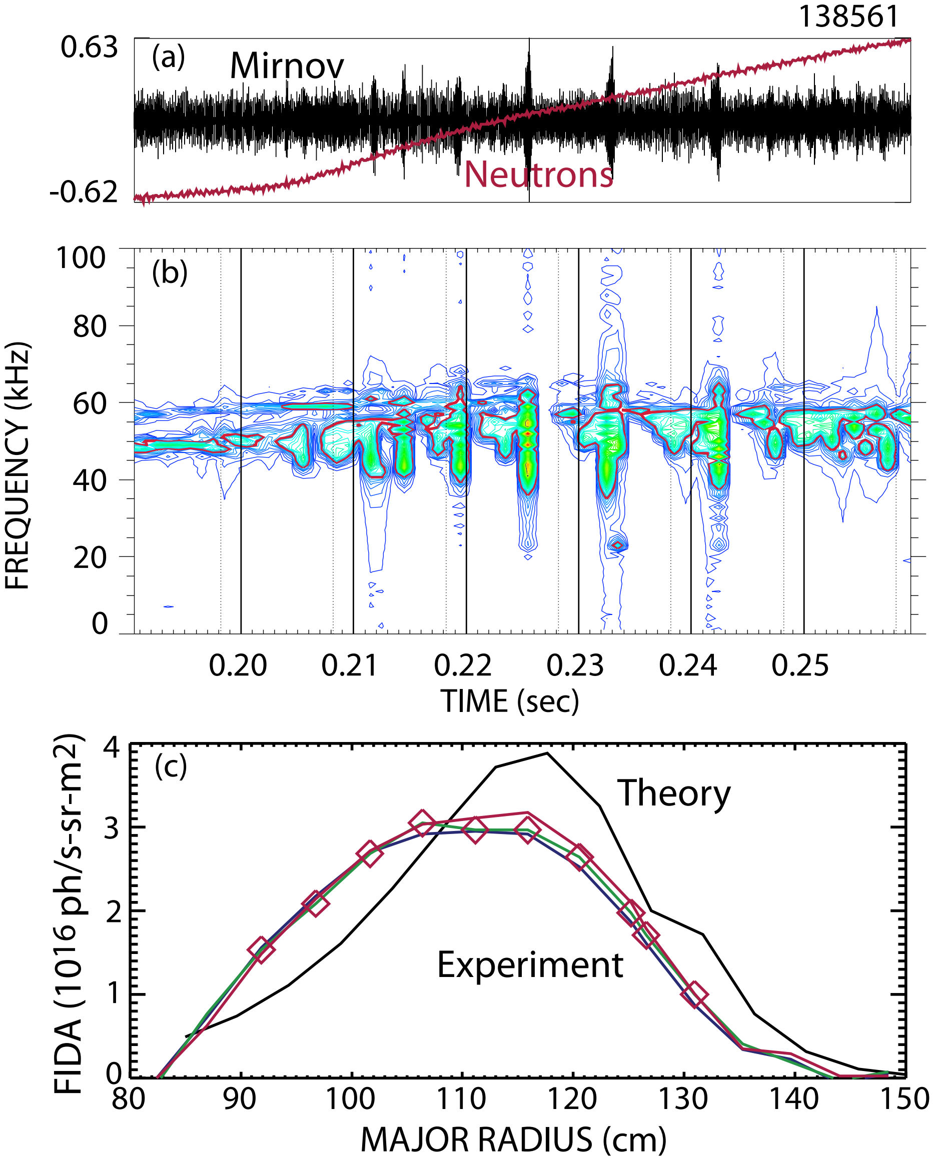
- **Nearly all cases show flattening**
- **No systematic change in spectral shape**
- **Consistent with Darrow’s conclusion that losses are broadly distributed in phase space**

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!