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Analysis of FIDA data from NSTX

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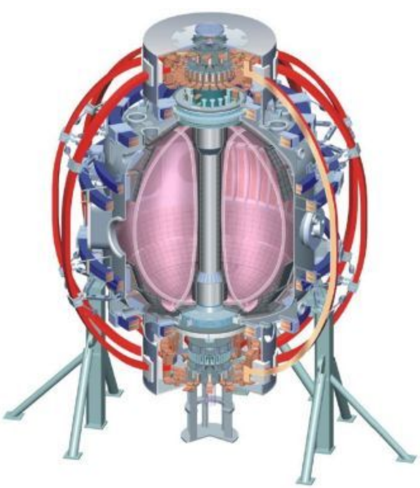
June 22, 2015



Supported by U.S. DoE under contracts DE-AC02-09CH11466 and DE-FG02-06ER54867

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

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

- **We extend this database with data from the vertical Fast Ion D_α (FIDA) diagnostic, and corresponding FIDASIM simulations which assume no beam ion loss.**

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

Fredrickson classified the different types of instabilities

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

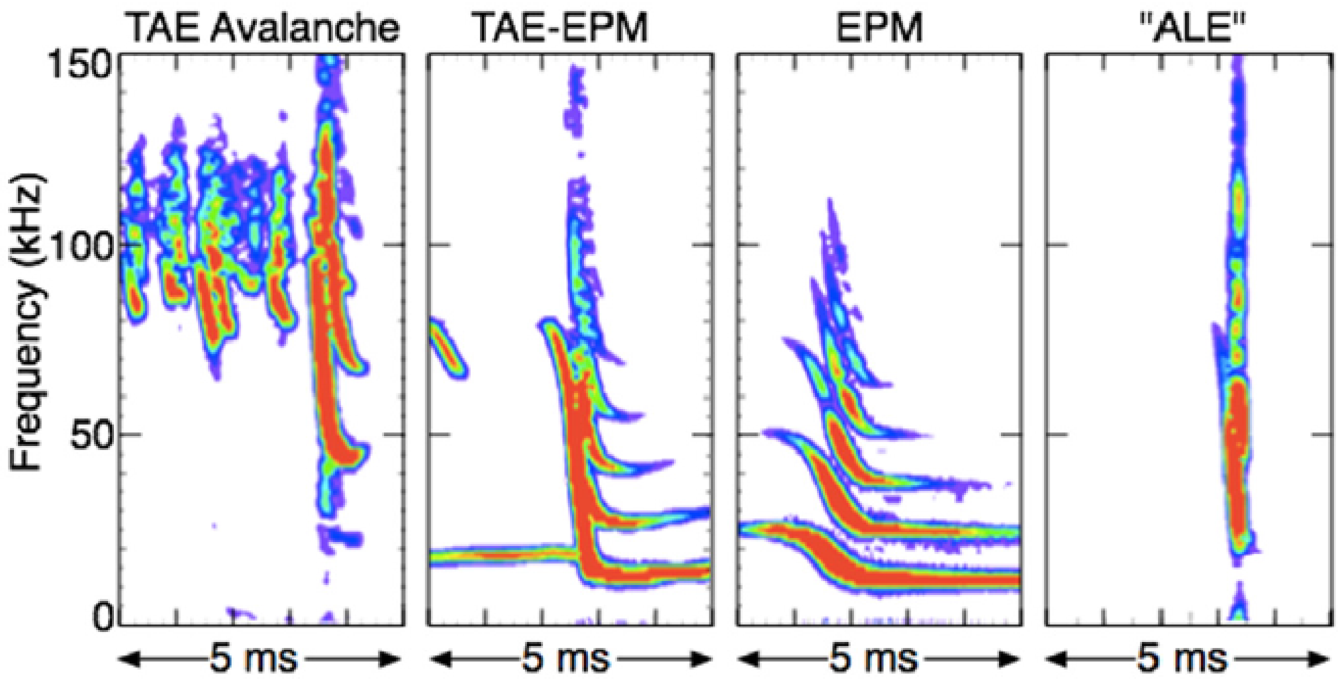


Figure 2. (*a*) Spectrogram showing a TAE avalanche, (*b*) spectrogram showing a hybrid TAE avalanche and EPM, (*c*) spectrogram of an EPM avalanche and (*d*) spectrogram of an ALE.

Eric found where the various instabilities occur in parameter space

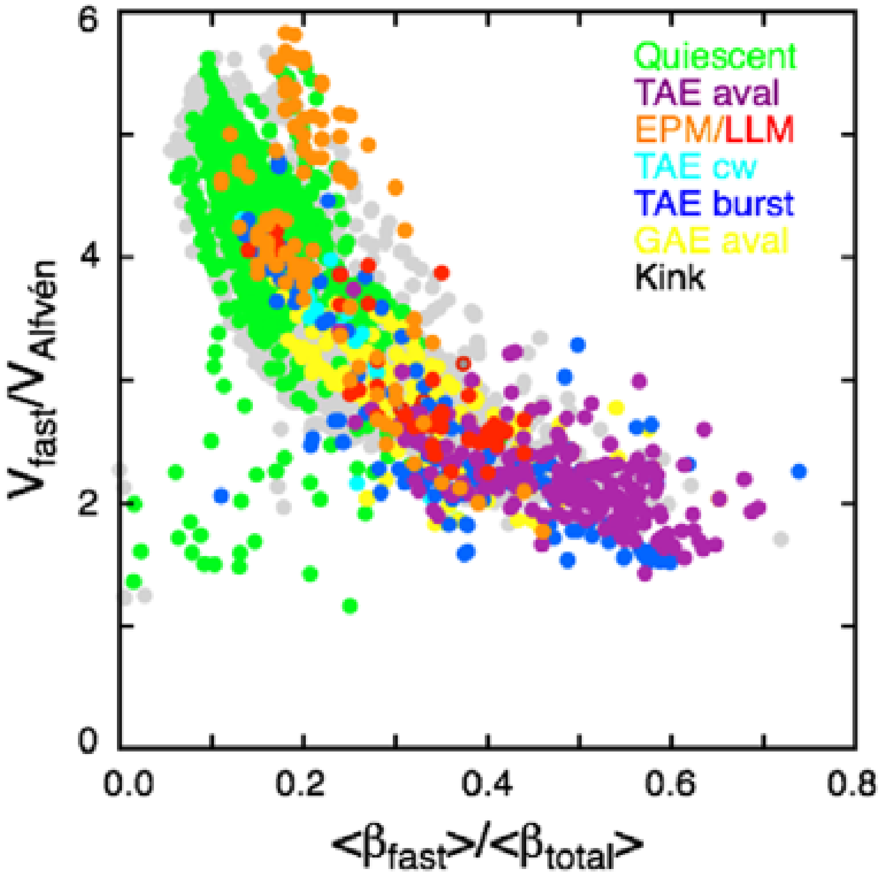


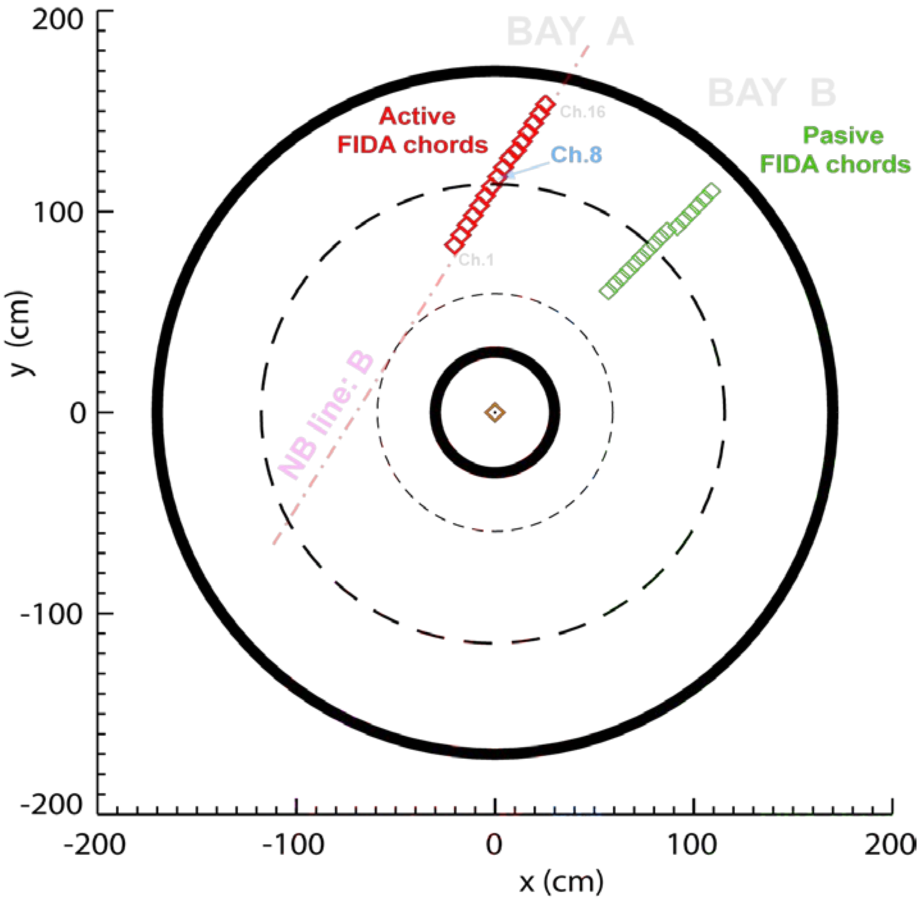
Figure 3. Existence plot for a variety of MHD activities.

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

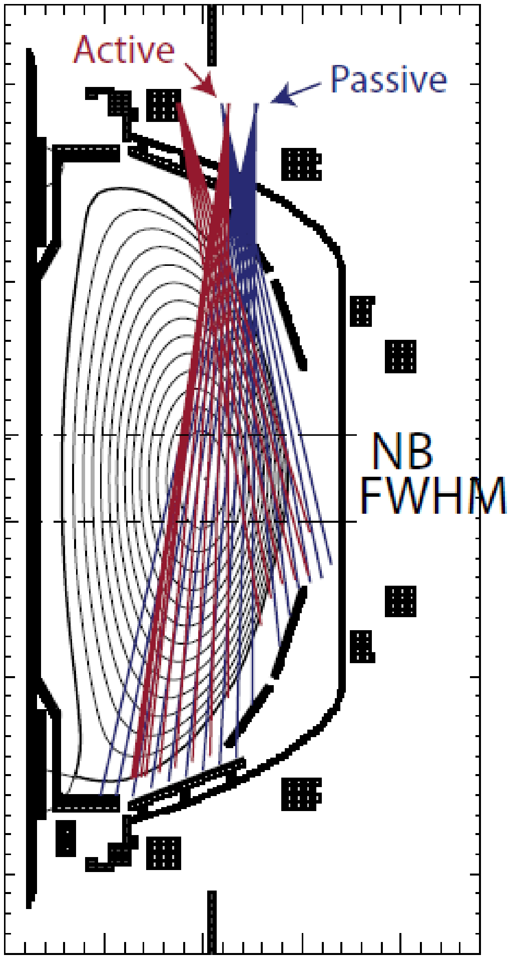
E. Fredrickson *et al.*, "Parametric dependence of fast-ion transport events on the NSTX"," Nucl. Fusion 54 (2014) 093007

Vertical FIDA data were routinely archived in 2010

Plan view



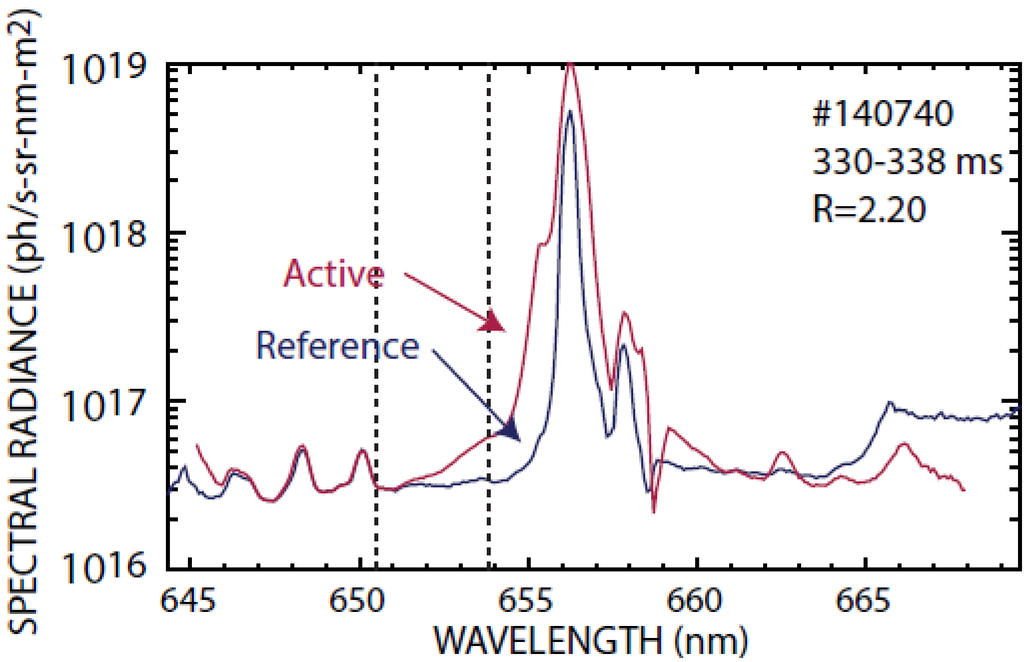
Elevation



Outline

- Construction of the Database
- General Trends
- Effect of ALE, TAE avalanche, EPM, and steady TAEs
- Conclusions

Use the net signal on the blue-shifted side

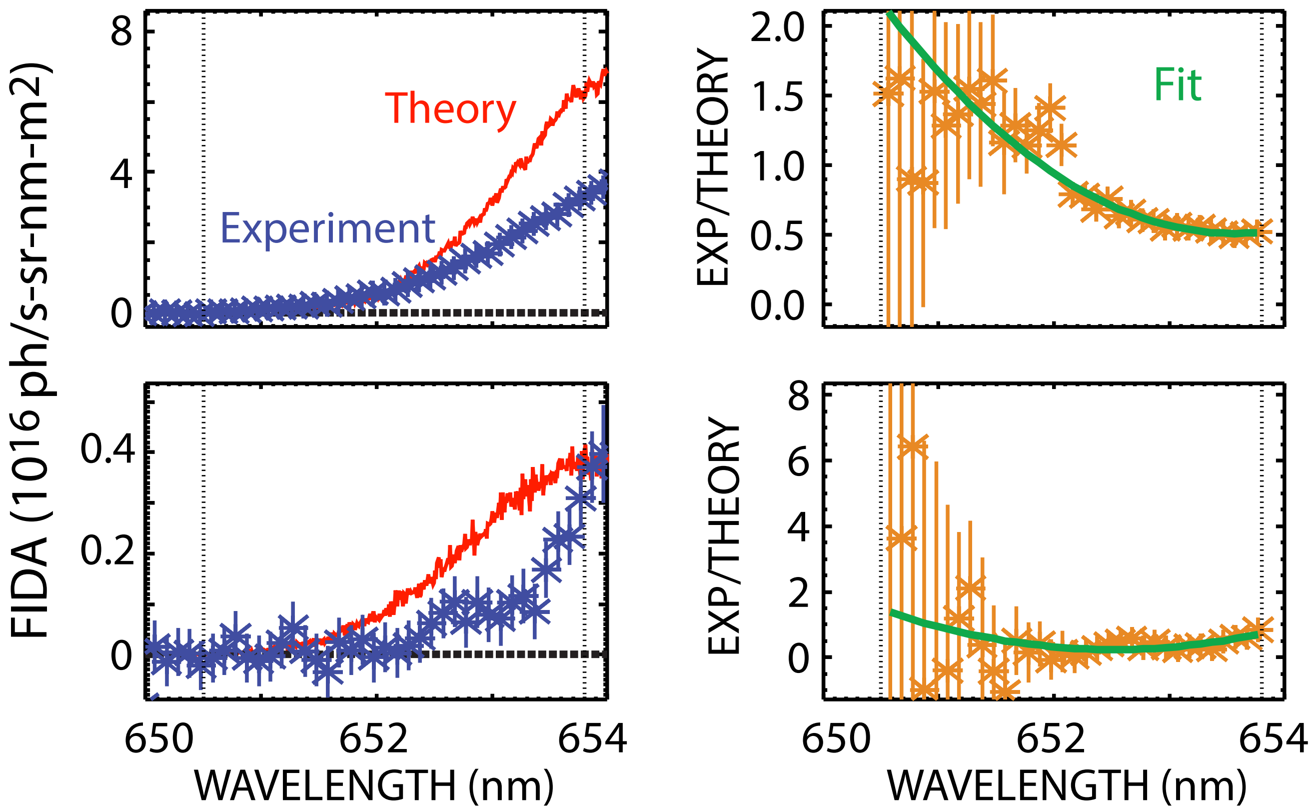


- The FIDA light is the difference between the active and passive views
- Wavelengths of interest are between the dotted lines
- The red-shifted side is ignored

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

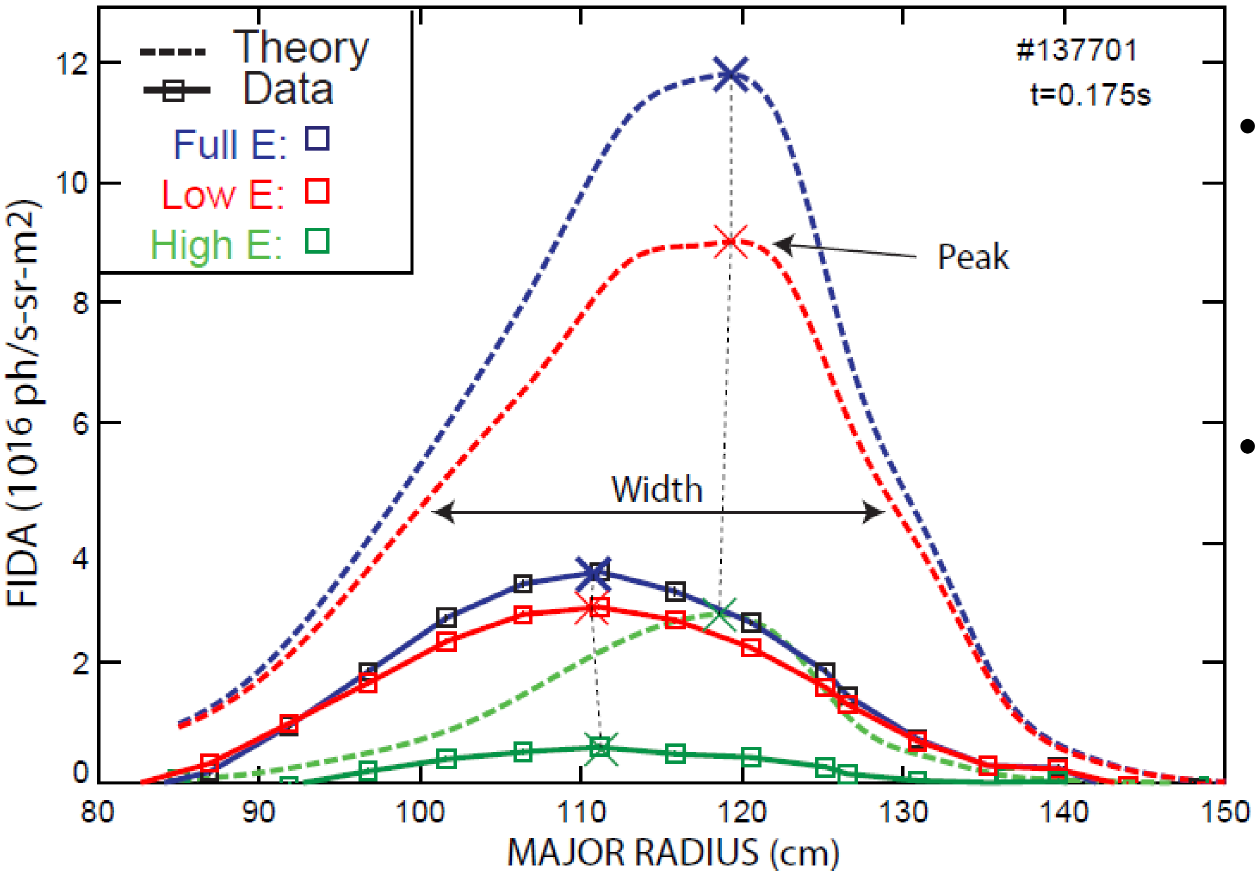


- **Compare data with "null hypothesis"**
- **Upper row has $\chi^2 \sim 420$; lower $\chi^2 \sim 1$**
- **Use quadratic fits to look for systematic discrepancies at low/high Doppler shift**

Theory spectra are:

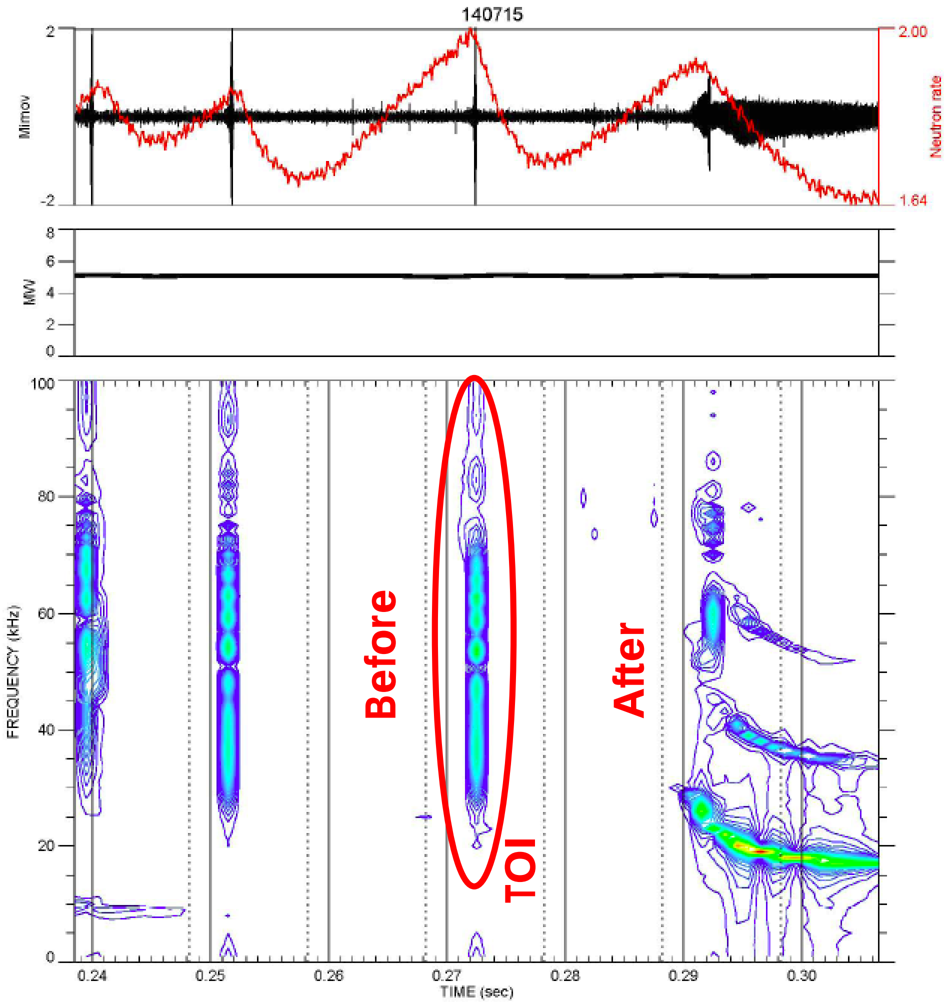
1. Smoothed with an instrument broadening function and mapped to the experimental lambda grid
2. Fitting is done over the full E_1 energy range, i.e. 650.5-653.8nm (dashed vertical lines)

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 (last ~1.8 ms of bin)
- Analysis times carefully selected
- Note in database whether activity is persistent, an isolated burst, etc.

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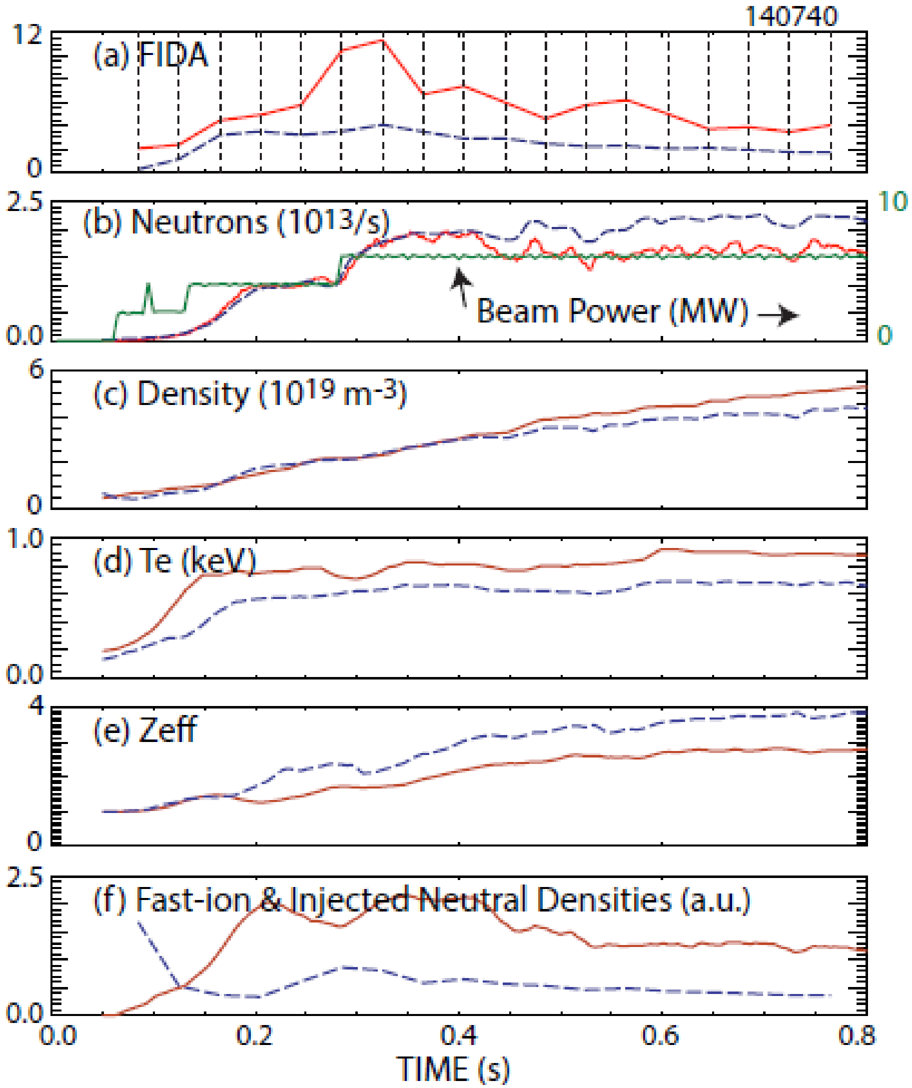
Time evolution of a representative shot



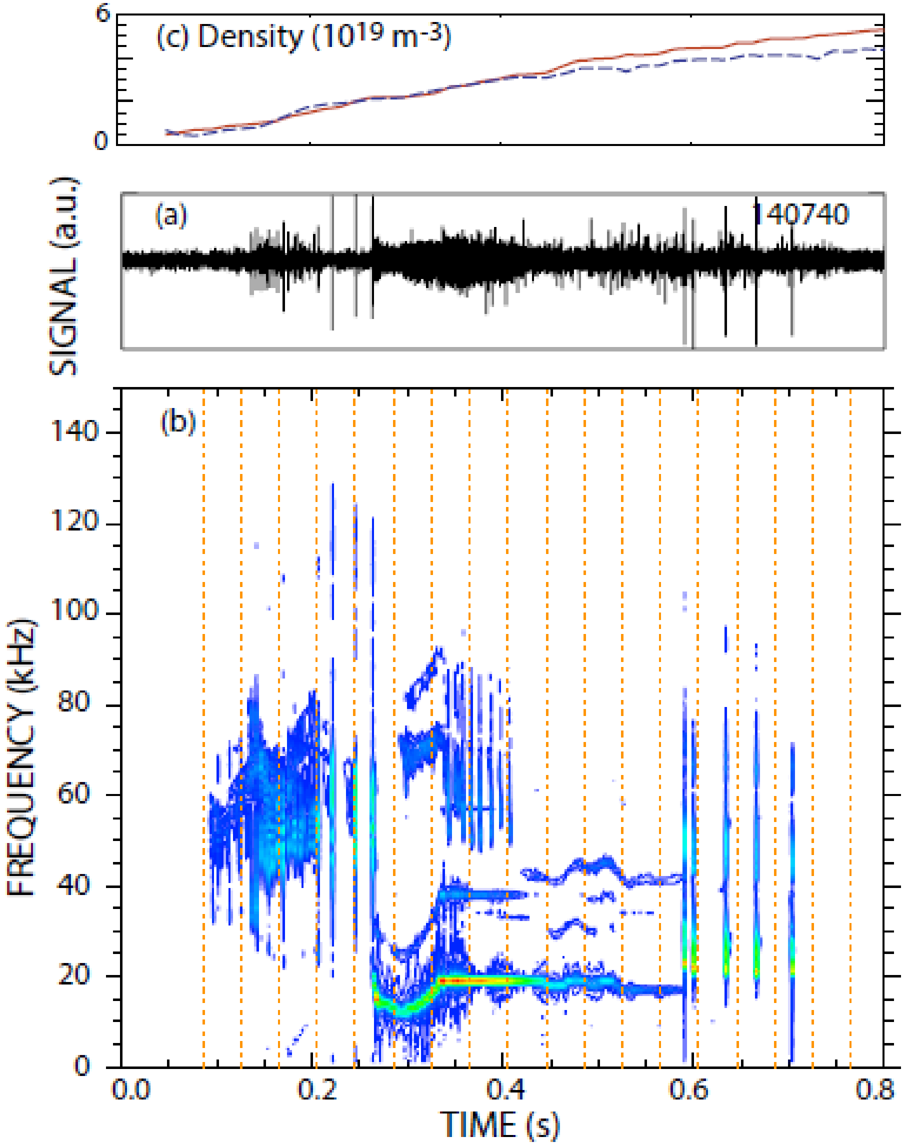
(a) Peak radiance in theory & experiment

(b) Neutrons in theory & experiment

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

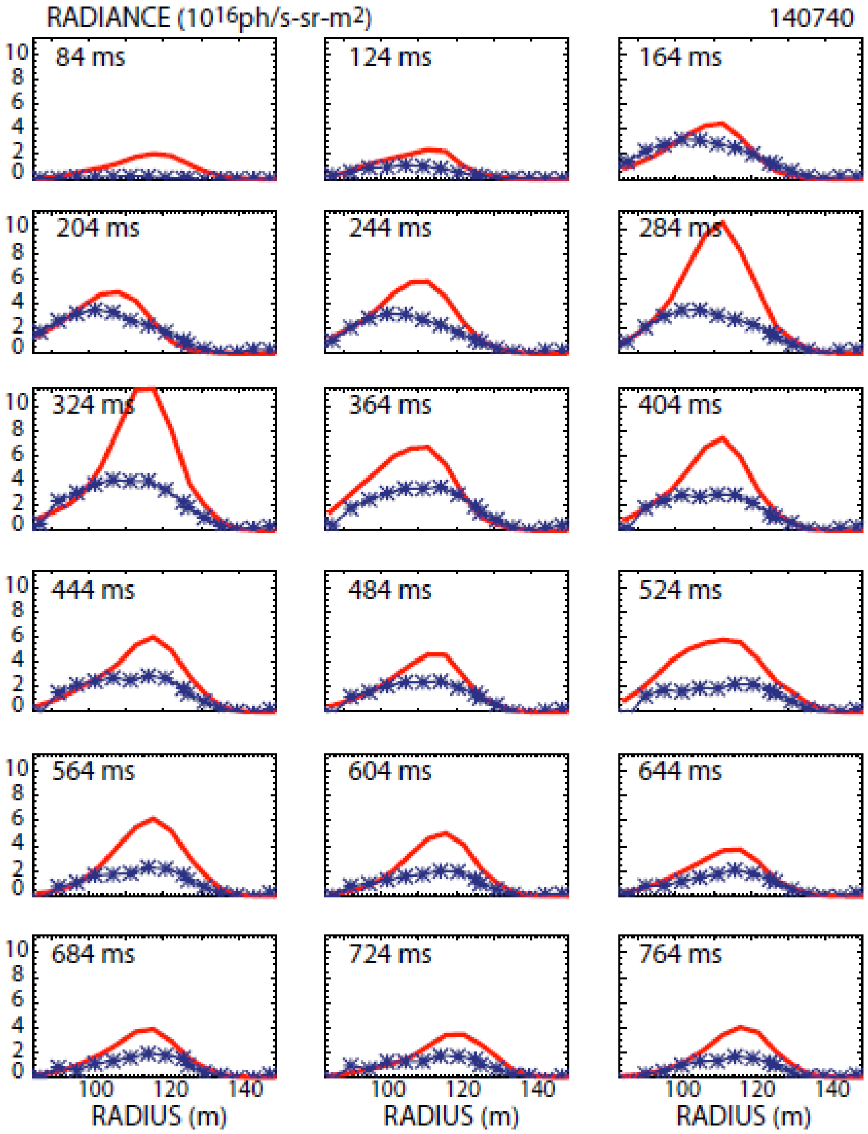
(f) Calculated fast-ion and injected-neutral densities at R=1.2 m

MHD activity in the representative shot



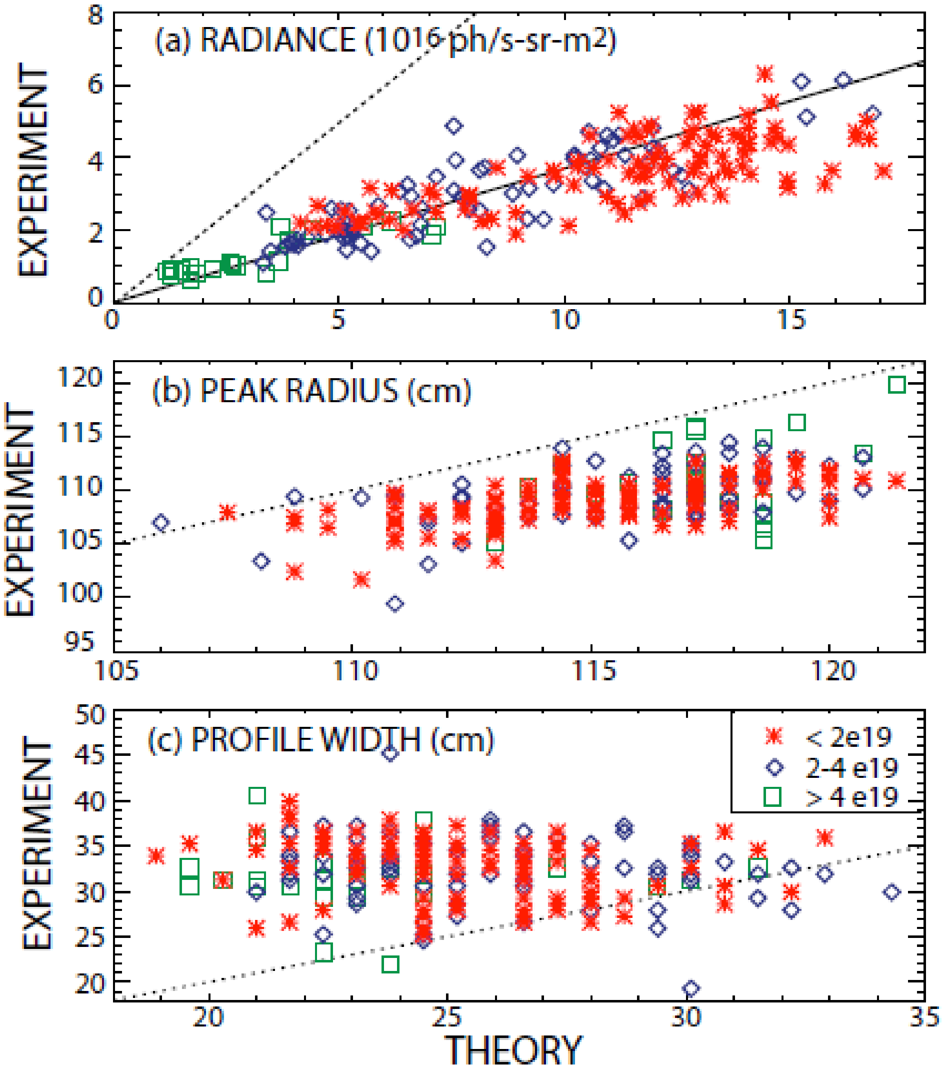
- **Wide variety of MHD but the correlation with the general trends in the FIDA data is weak**

FIDA profiles show persistent trends throughout the shot



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

FIDA profiles show persistent trends throughout the database



- **On average, the peak radiance is 0.37 of theory but strongly correlated (r=0.88)**
- **Agreement best at higher n_e (lower β_f, slowing-down time)**
- **Weak correlation with other plasma parameters**
- **Peak radius is 109 ± 3 cm in experiment but 115 ± 3 cm in theory**
- **Experimental profile 30% wider than theory**
- **Similar results for other wavelength ranges**

What causes this discrepancy?

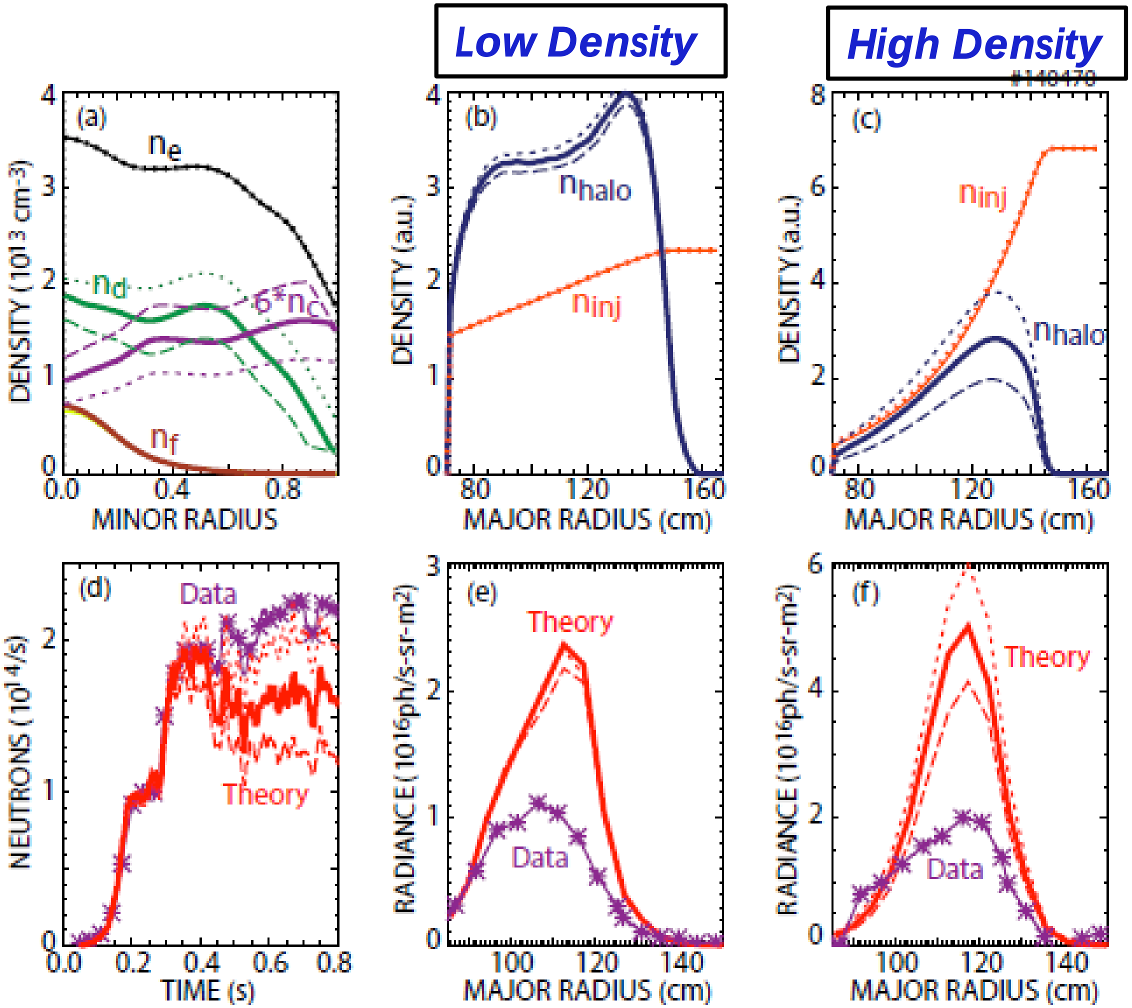
1. **Procedure is flawed. No. The same procedure works well for DIII-D and ASDEX-Upgrade.**
2. **Experimental calibration is wrong. Unlikely. (Hard to get both magnitude & shape wrong)**
3. **Inputs to theory are wrong.**

   (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.
4. **Charge exchange losses are underestimated. No.**
5. **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

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 magnitude & shape wrong systematically)**
3. **Inputs to theory are wrong.**
   (a) Beam power or T_e. No. (Makes neutron agreement worse.)
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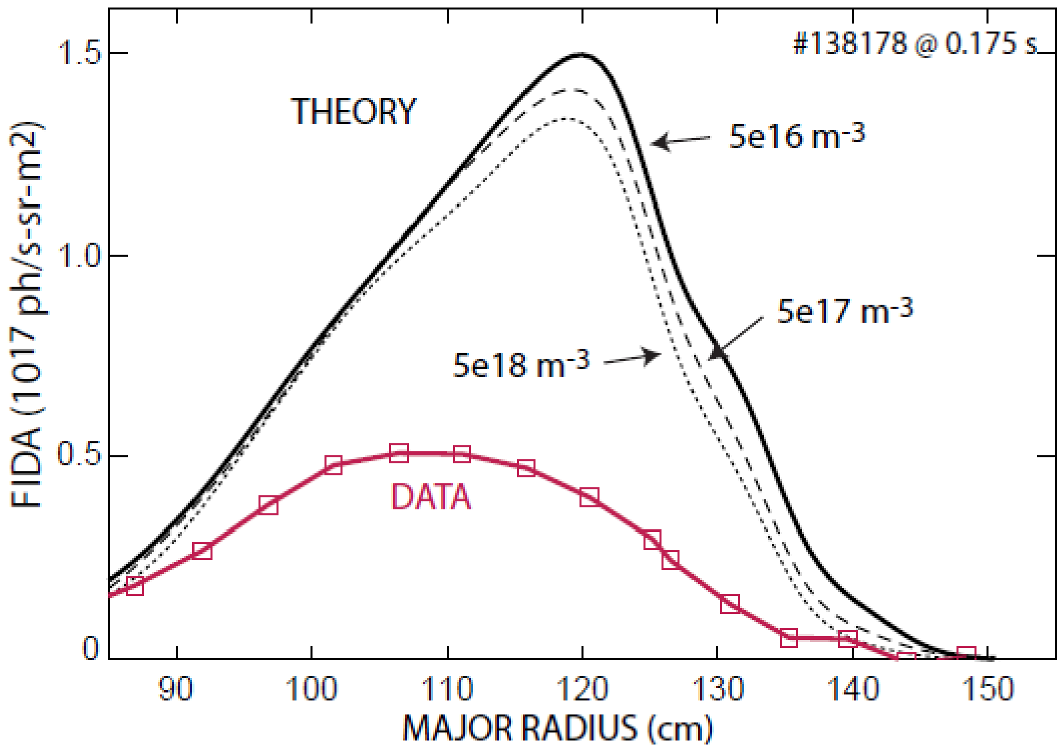
   (c) Zeff. No.
4. **Charge exchange losses are underestimated. No.**
5. **An unidentified process redistributes the fast ions. Probably. (Product of peak*width agrees better than either individually; better agreement at higher n_e expected.)**

Edge charge-exchange losses cannot explain discrepancy



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

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 magnitude & shape wrong systematically)
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.
4. Charge exchange losses are underestimated. No.
5. An unidentified process redistributes the fast ions. Probably. (Product of peak*width agrees better than either individually; better agreement at higher n_e expected.)

What could this unidentified process be?

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

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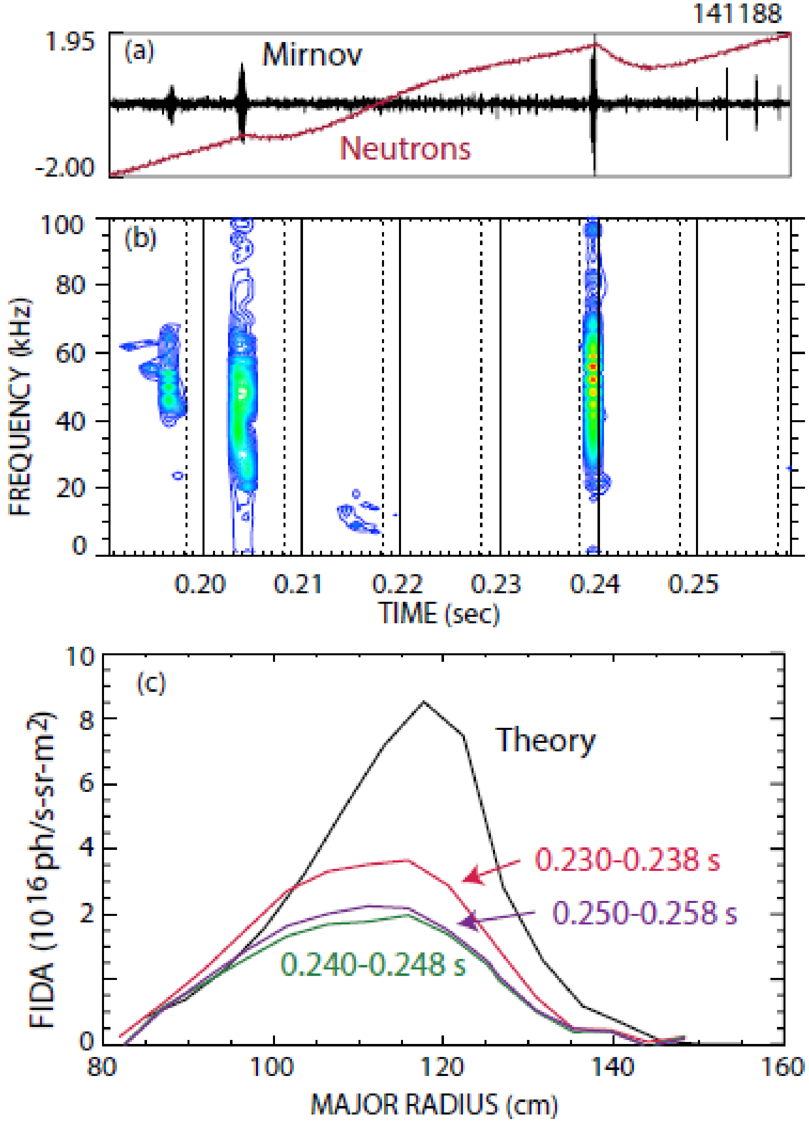
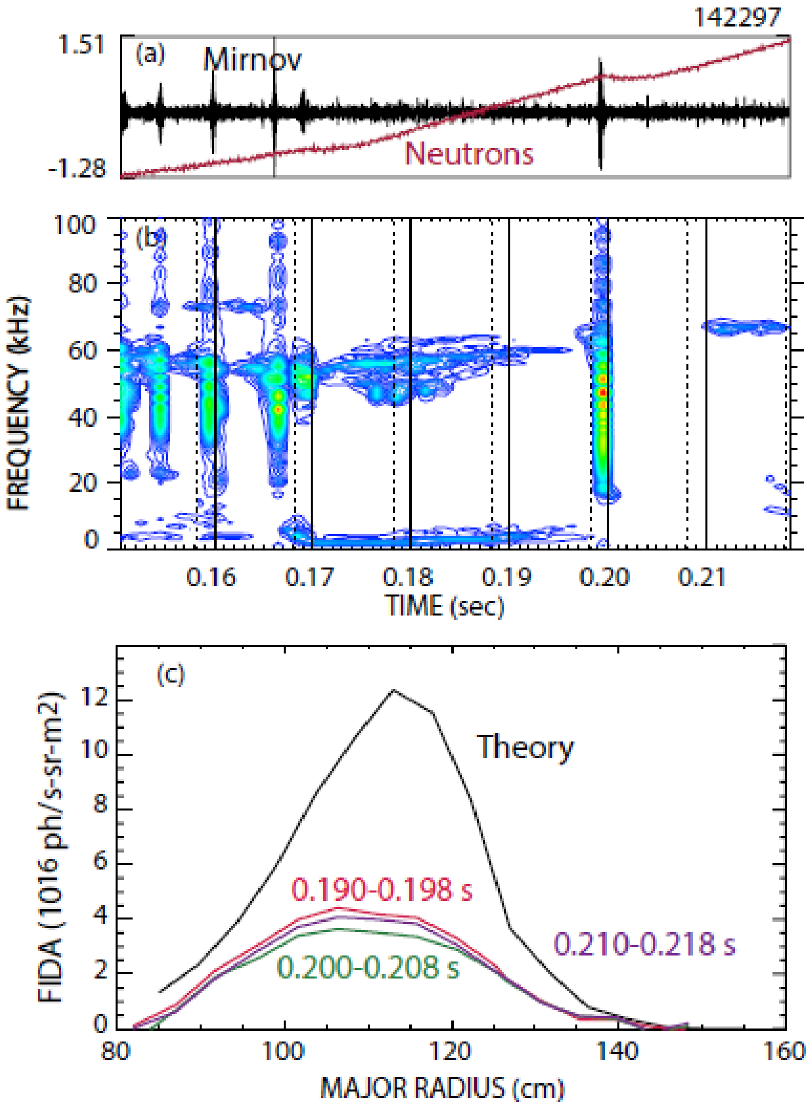
Every ALE causes profile flattening



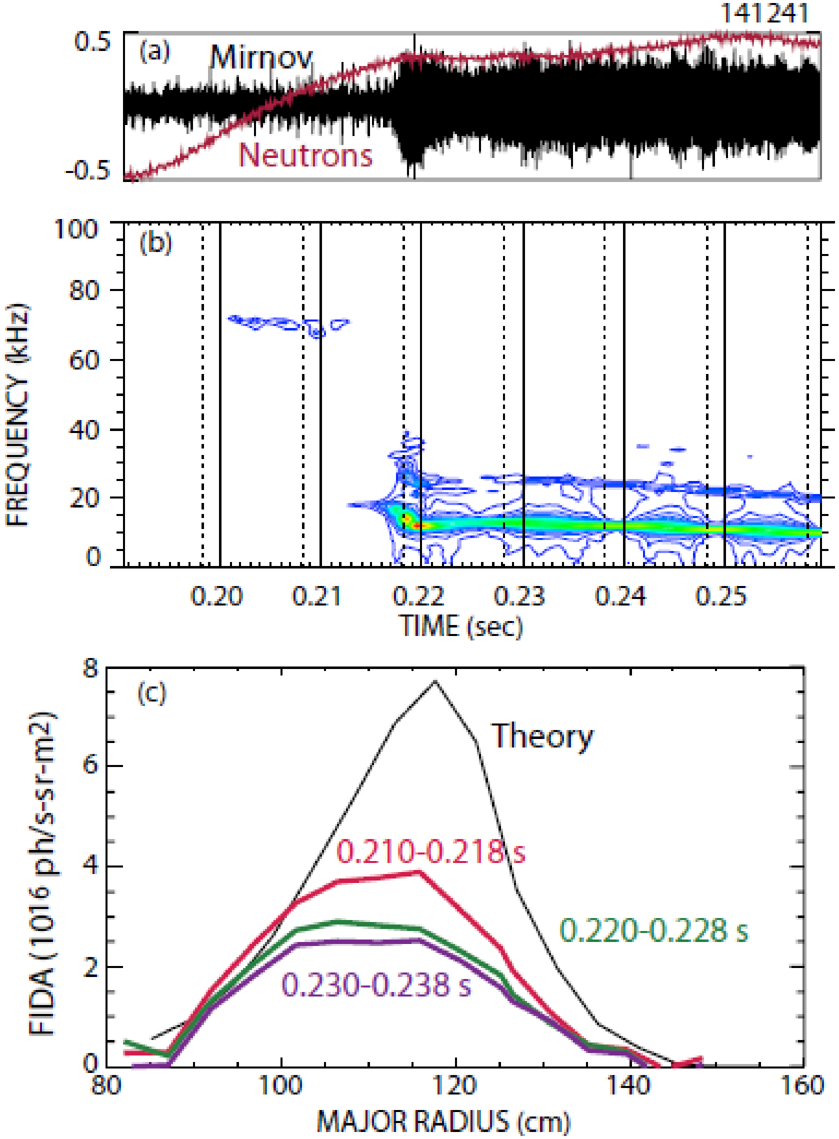
- **Profile immediately after the burst is 0.81 ± 0.06 of prior profile.**
- **No systematic change in spectral shape**
- **Consistent with JT-60U neutron profile measurements and modeling**

TAE avalanches usually cause profile flattening



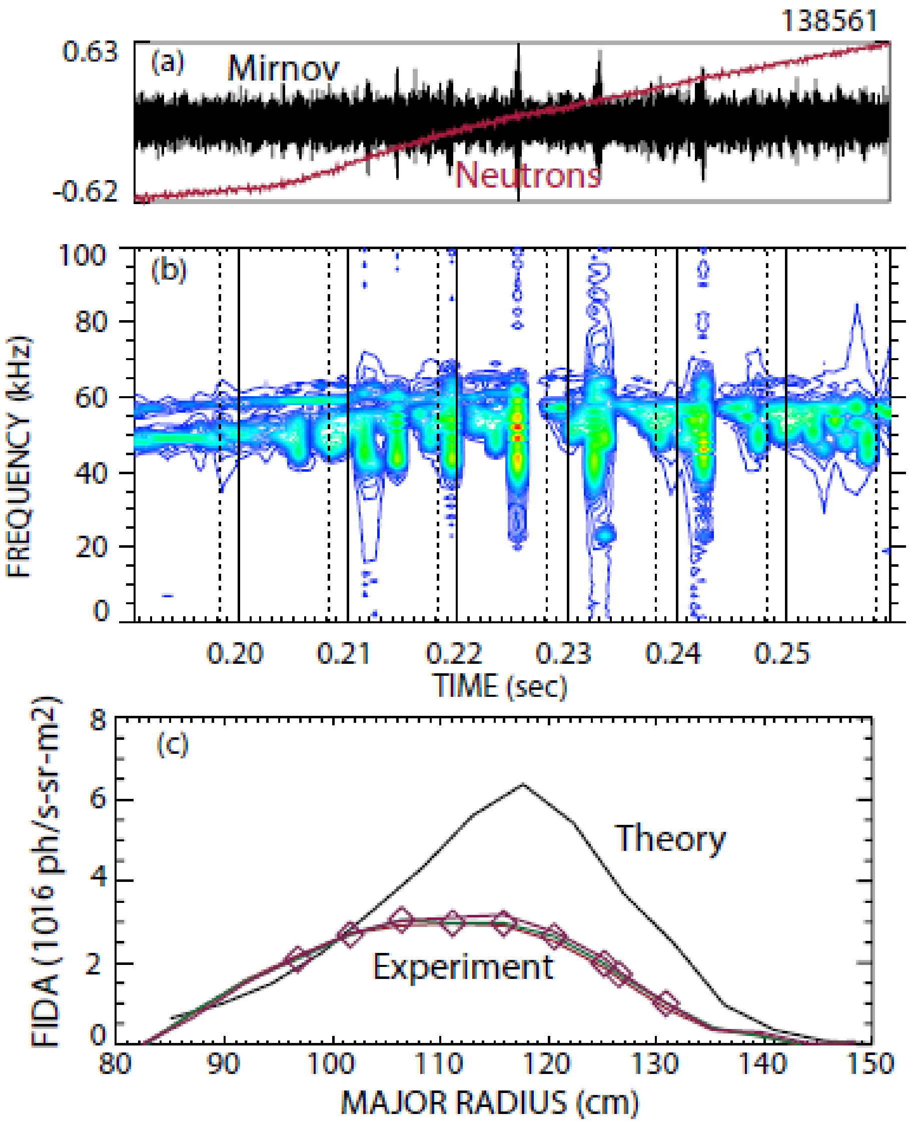
- **Nearly all cases show flattening**
- **No systematic change in spectral shape**
- **Consistent with Darrow's conclusion that losses are broadly distributed in phase space**

EPMs cause profile flattening



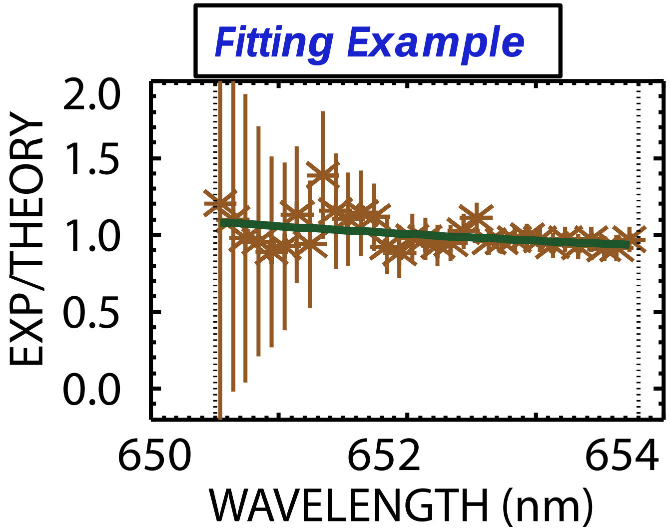
- **Flattened profile persists in subsequent time slices**
- **No systematic change in spectral shape**

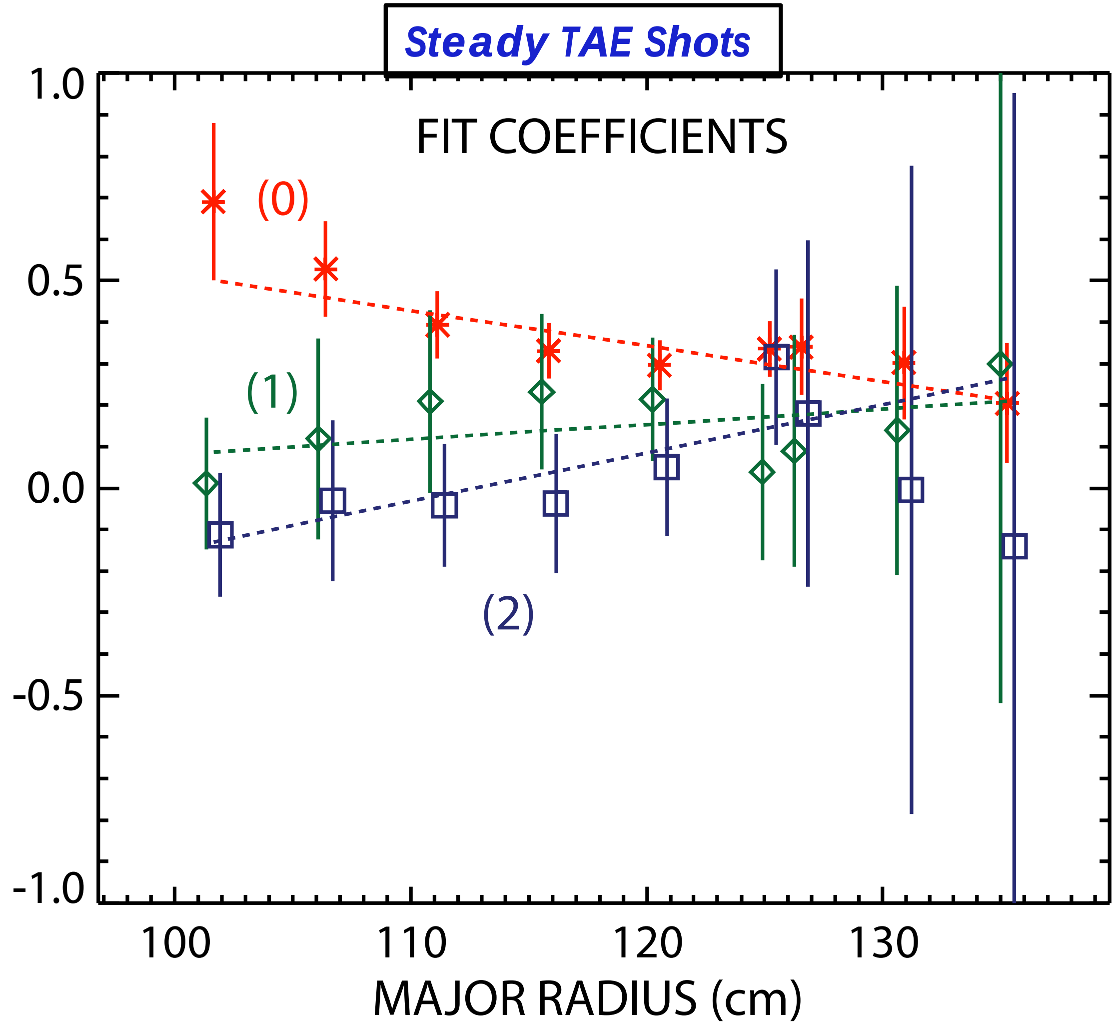
TAEs are too rapid to detect effect of individual events



- **As expected, successive time bins are virtually identical**
- **Agreement good at small major radius but poor at large major radius**

There is a shortfall of high energy ions at large major radius in the TAE shots





- **Fit to a quadratic**
- **Perfect agreement: (0) =1; (1) & (2) = 0**

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.
- There is a shortfall of high-energy fast ions at large major radius during TAEs.

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