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The Effect of Different Fast-ion Instabilities on the Fast-ion Profile

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E. Fredrickson, M. Podestà, A. Bortolon PPPL

56st Annual Meeting of the Division of Plasma Physics
New Orleans, Louisiana
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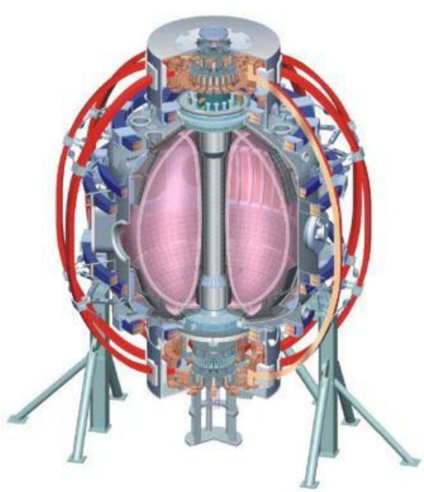

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MOTIVATION

- **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:**

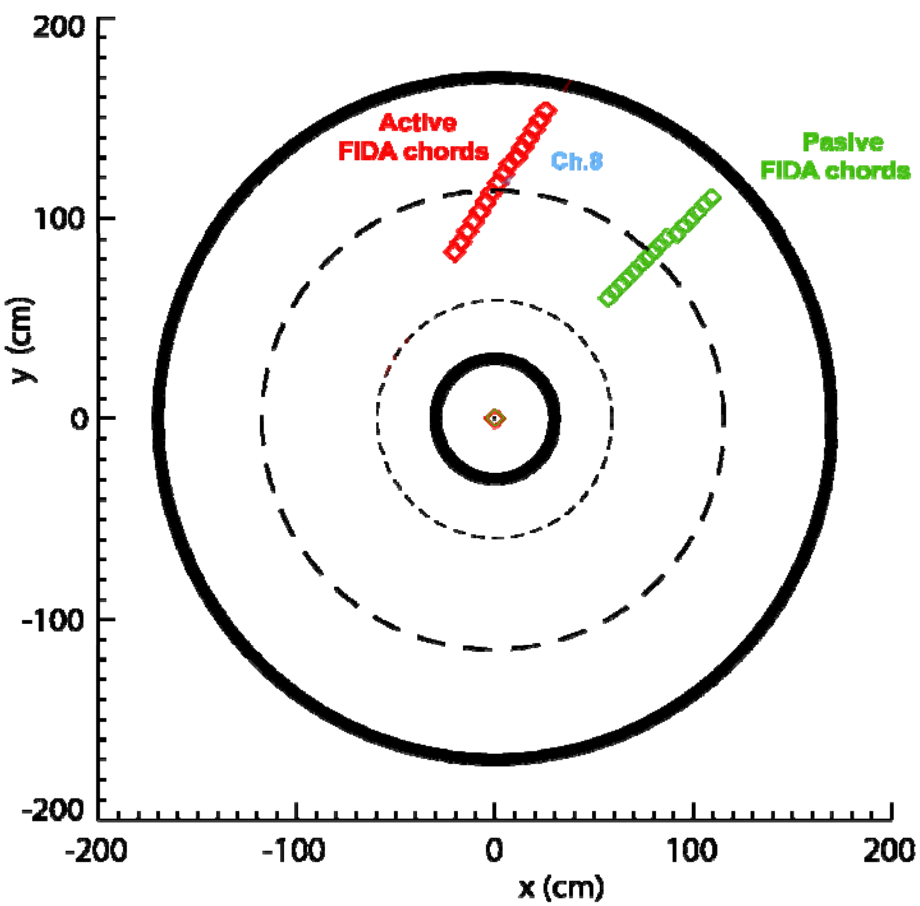
$$\langle\beta_{fast}\rangle / \langle\beta_{total}\rangle \qquad V_{fast} / V_A \qquad \delta S/S \qquad \delta B/B$$

- **We want to extend this database with data from the vertical Fast Ion D_α (FIDA) diagnostics, and corresponding FIDASIM simulations which assume no beam ion loss.**
- **Here we present a progress report on this work and some representative new parameters, together with beam profile examples illustrating the effect of these instabilities.**

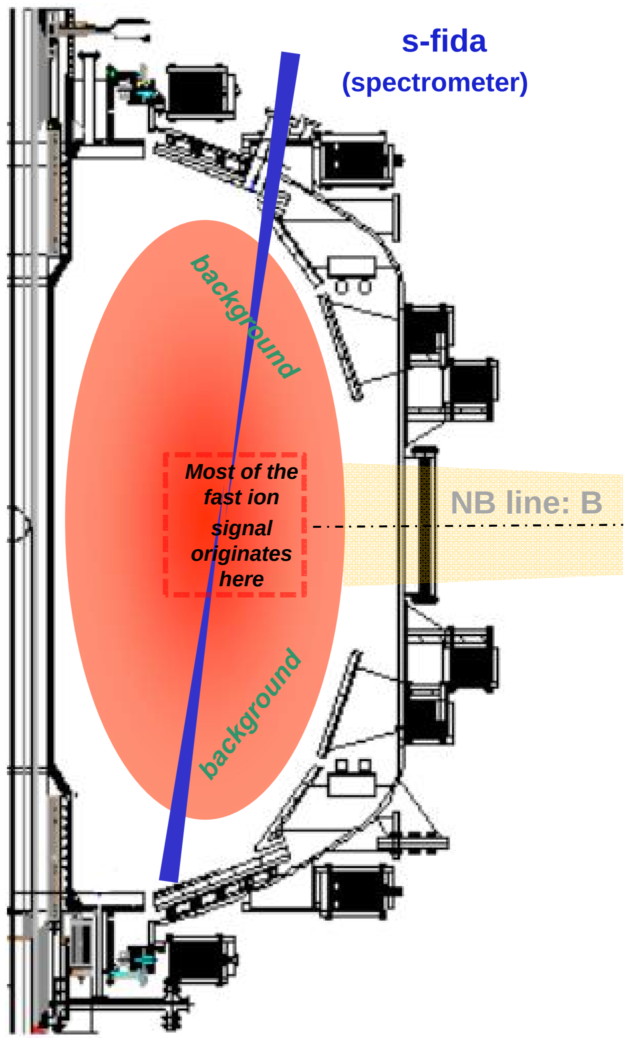
* E. Fredrickson *et al.*, "Parametric dependence of fast-ion transport events on the NSTX"," Nucl. Fusion 54 (2014) in press

Overview of the FIDA system geometry at NSTX

Top view

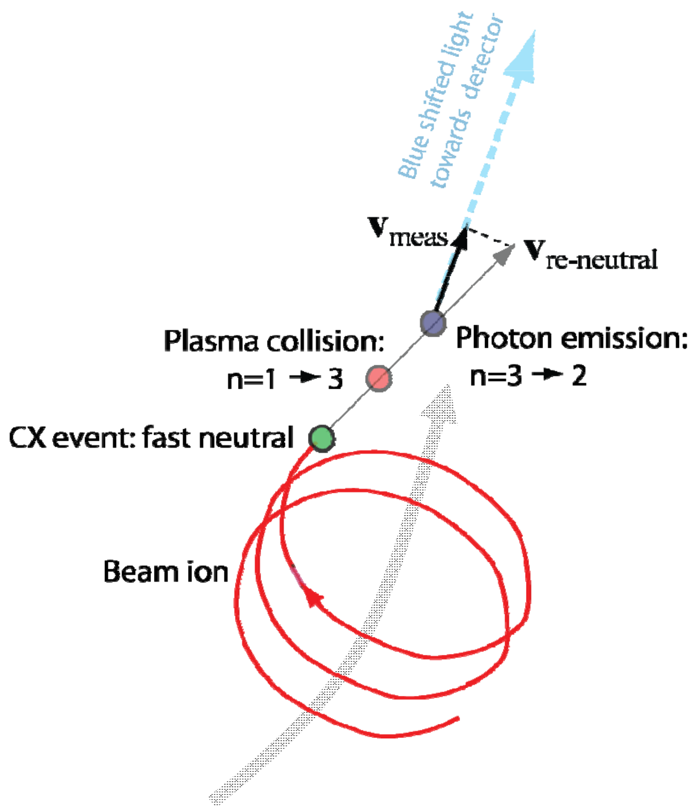


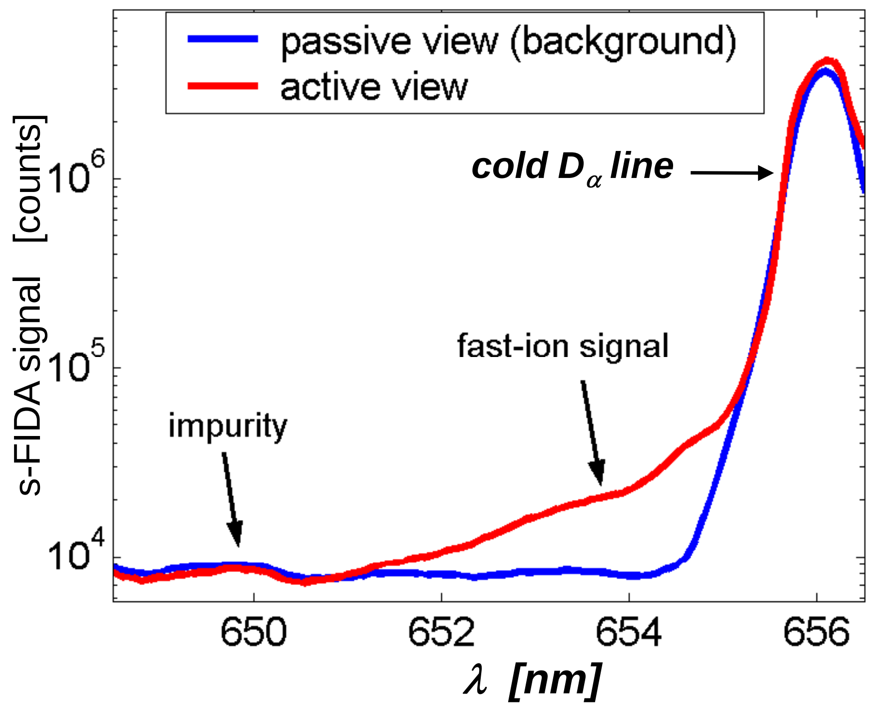
Vertical view



Beam ions are diagnosed through active charge-exchange D_α spectroscopy (FIDA technique)

- Photons emitted by re-neutralizing fast ions (interacting with the beam and halo neutrals) have Doppler shifted wavelengths vs. the cold D_α line
  - Key is distinguishing fast-ion features from the dominant cold D_α emission
- Passive views miss the neutral beam - used for background subtraction

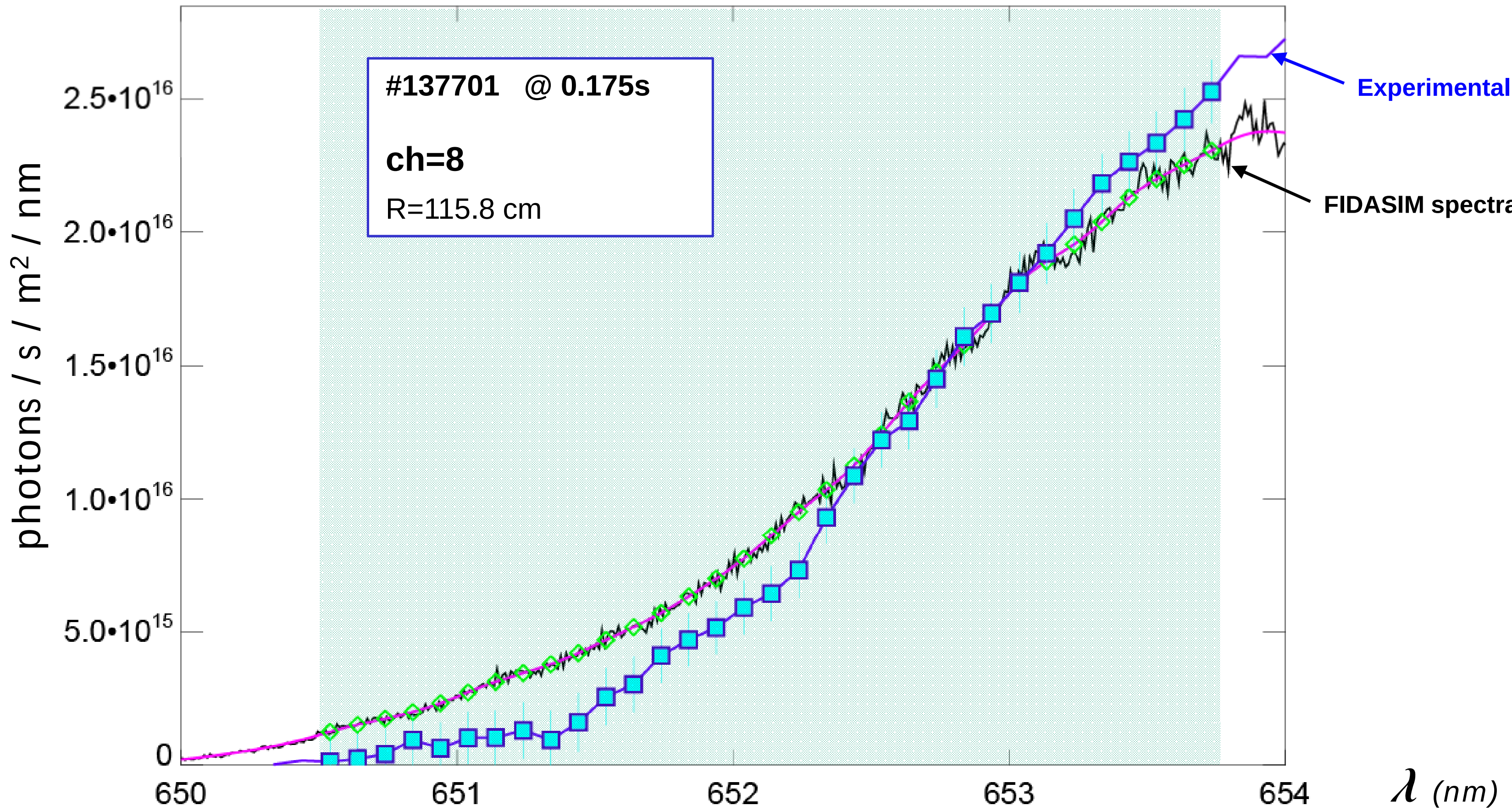




Theory spectra and FIDASIM code

- **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.**

Fitting theory to measured spectra



Theory spectra are:

1. Smoothed with an instrument broadening function and mapped to the experimental lambda grid
2. Least square fitting is done over the full E_1 energy range, i.e. λ=650.5-653.8nm (shaded area)

Spectra related new database parameters

For each channel:

- The scalling factor and reduced χ^2 from the fitting of theory to experimental spectra are saved (two numbers).

- Theory spectra shape deviation from the XP is quantified with nonliner fitting. A parabolic function $c_0 + c_1\lambda + c_2\lambda^2$ is calculated and the fitting error, scaling factor and c_0, c_1, c_2 coefficients are saved (five numbers). The larger this deviation, the larger the possible effect of the MHD instability on beam ion confinement.

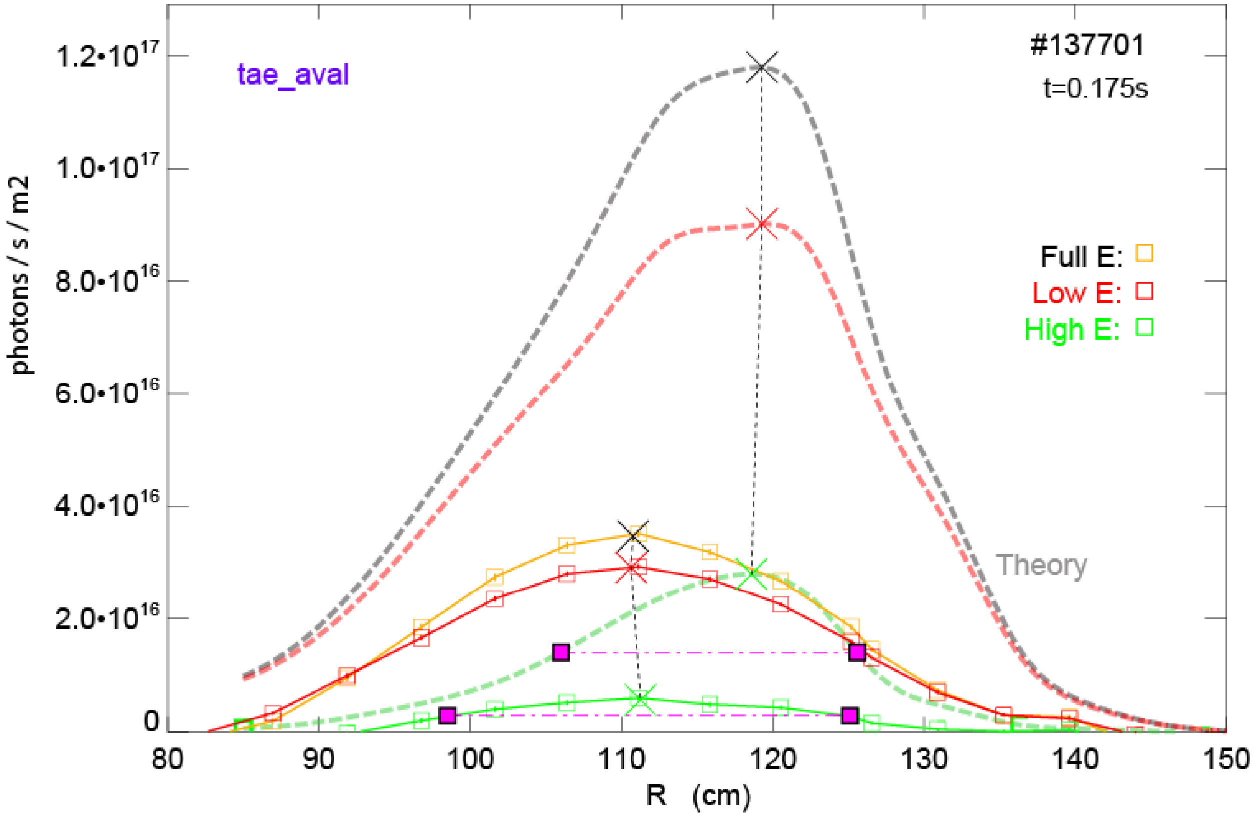
- A hypothesis of zero value XP spectra is tested:

$$\chi_0^2 = \Sigma \; (A_i \,/\, Err_i)^2 \,/\, N$$

summation is over the N wavelenghth data points in [650.5, 653.8]nm

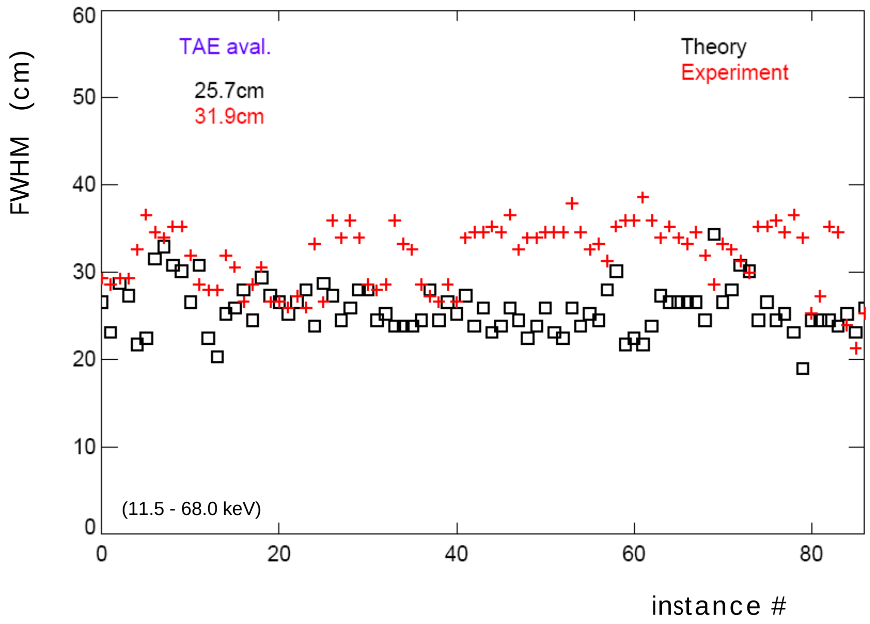
The saved number is intended for filtering bad experimental data which are present in about 30% of shot_time instances. In another ~20% of the instances the 2-3 innermost and/or outermost channels also have poor S/N.

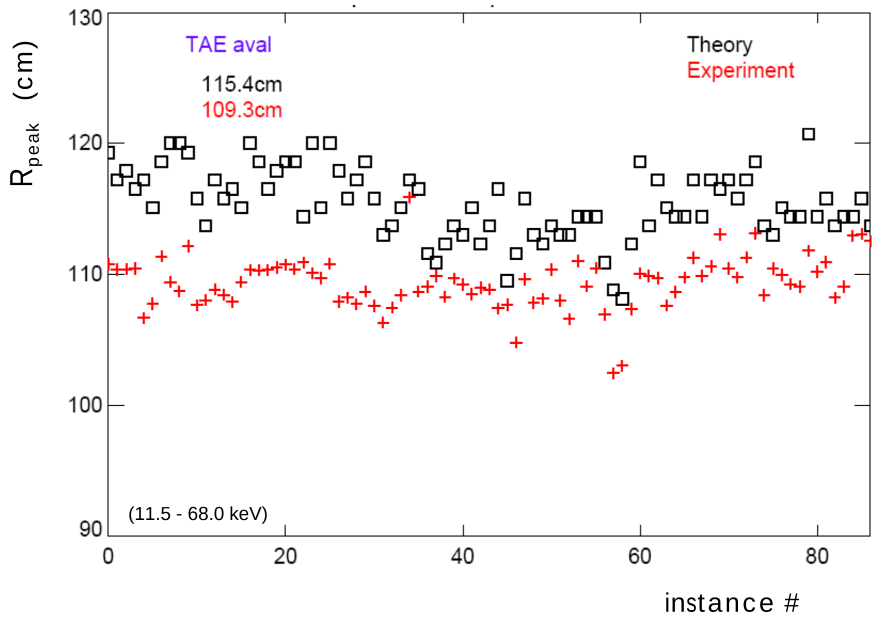
Profiles and their parameters



- Theory and experimental profiles and their parameters are calculated for 3 energy ranges:
  full (11.5-68.0 keV), **low** (11.5-31.3) and **high** (31.3-68.0 keV)
- Saved parameters are profile width, peak location and value
- Shape change is characterized by least square fitting(scale factor and reduced χ^2)
- In the majority of cases there is a factor of 2-3 discrepancy in the peak values for theory and experiment. The nature of this discrepancy is not understood at this time.

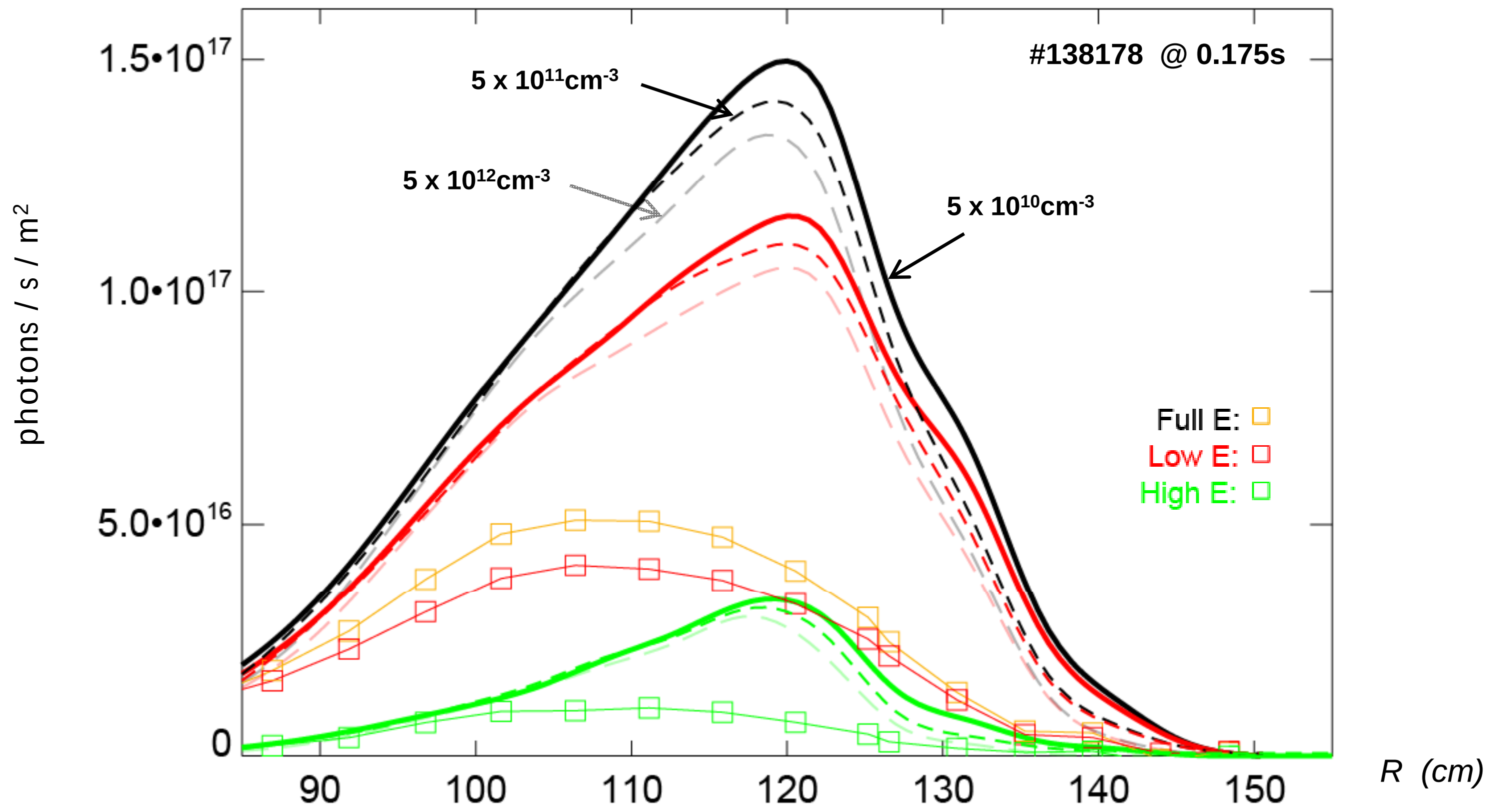
Experimental profiles are wider than simulated profiles





- Theory profiles are narrower in each of the three energy ranges considered and for all four considered types of instabilities: ALE, EPM, TAE and TAE avalanches. This is an indication of beam ion redistribution over a wide energy range.
- Average FWHM broadening of the full energy profiles varies from 15% (for TAE modes) to 33% (for Abrupt Large Events). For the TAE avalanches shown above the broadening is ~25%.
- Peaks of the experimental profiles are shifted inwards for each energy range and instability type. Average shift values for the 11.5 - 68.0 keV energy profiles is 4-5cm; individual cases do have 10+ cm shifts. The nature of these shifts is not understood at this time.

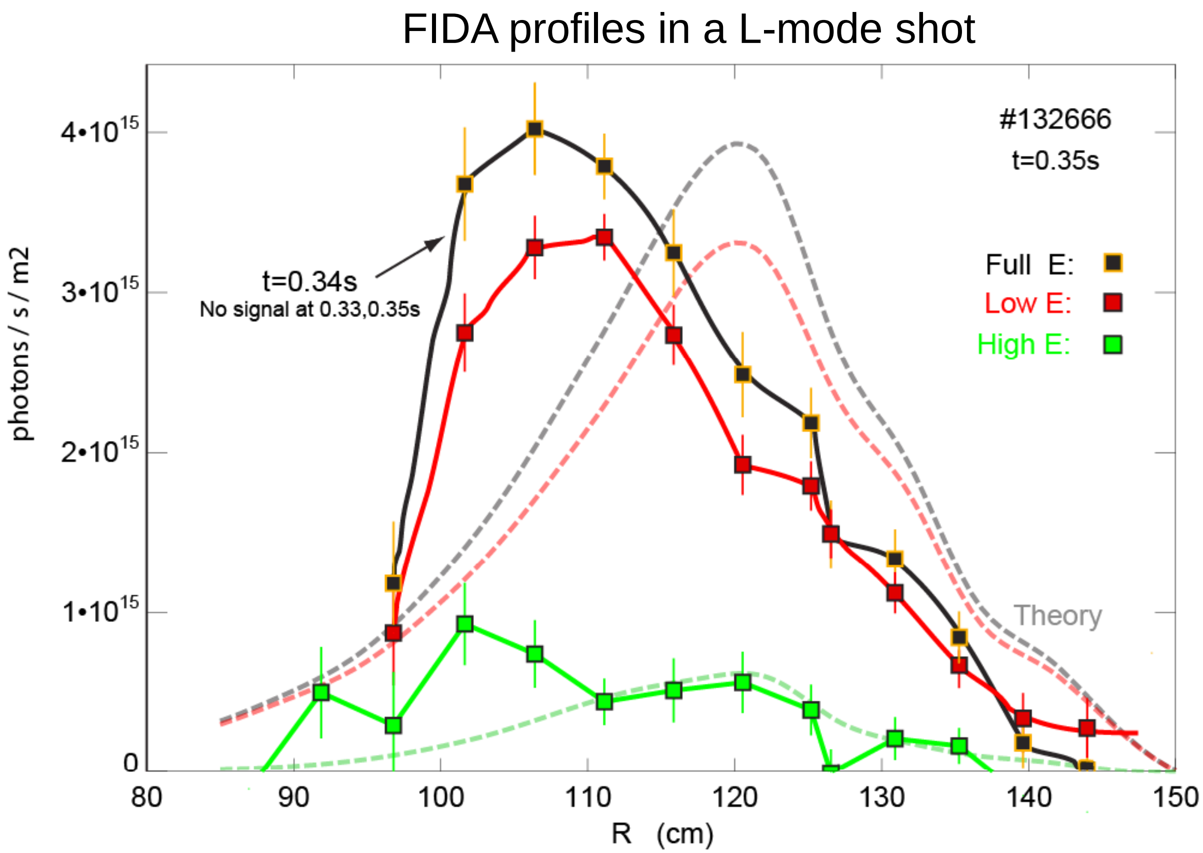
Neutral density uncertainty can be ignored

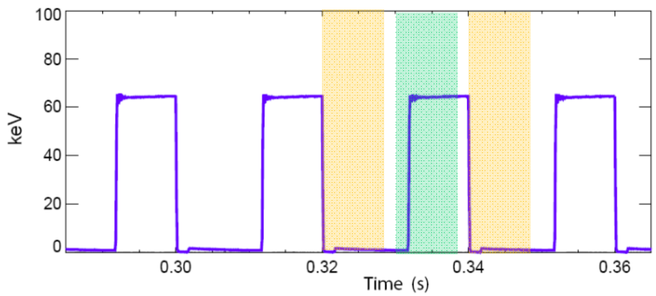


- Neutral gas density in the NSTX scrape off layer is not well known. DEGAS2 calculations indicate* values up to 10^{12} cm^{-3}. This systematic uncertainty in the FIDASIM modeling was addressed using TRANSP f_b from simulation with x10 and x100 increase of the nominal neutral gas density N_0= 5 x$10^{10}$$cm^{-3}$.
- Very small profile variations are observed on the high filed side. They increase somewhat on the low filed side reaching 40-50% drops at R=135cm, in this particular example.
- However, the calculated profiles shape, peak location and value are not substantially changed.

* D.P.Stotler *et al*., "Midplane neutral density profiles in NSTX" , P3-098 PSI conference

Illustration of s-FIDA Data Acquisition



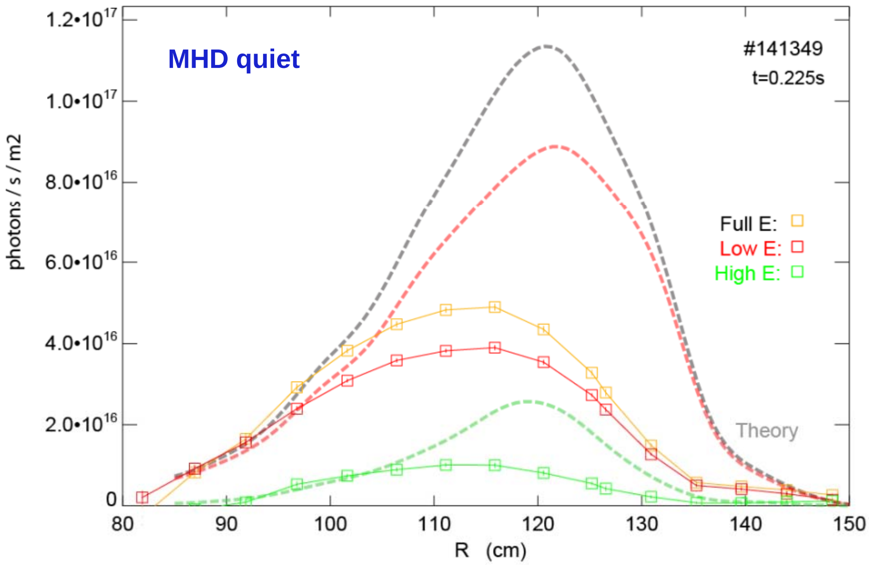


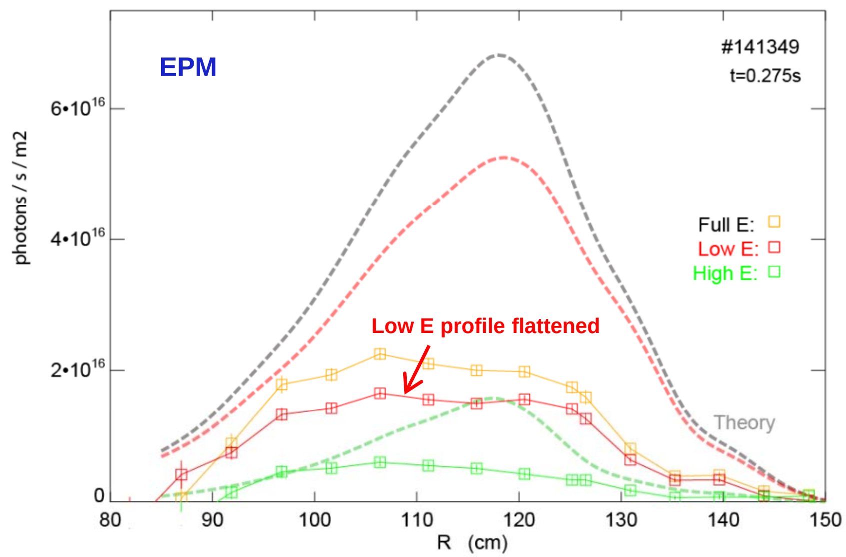
- s-Fida times (t=0.33, 0.34, 0.35) indicate ends of 10ms DAQ cycles
- The spectrometer lens is covered during the last 1.8ms in the cycle
- The exact location of the s-FIDA DAQ window is essential when analyzing fast instabilities

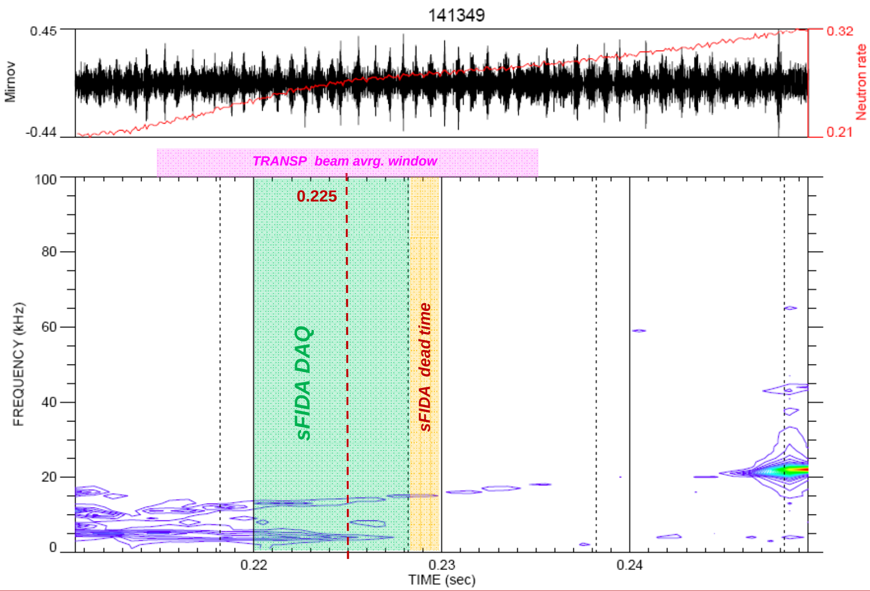
- Measured spectra are scaled with an absolute calibration factor* of 5 x 10^{12}

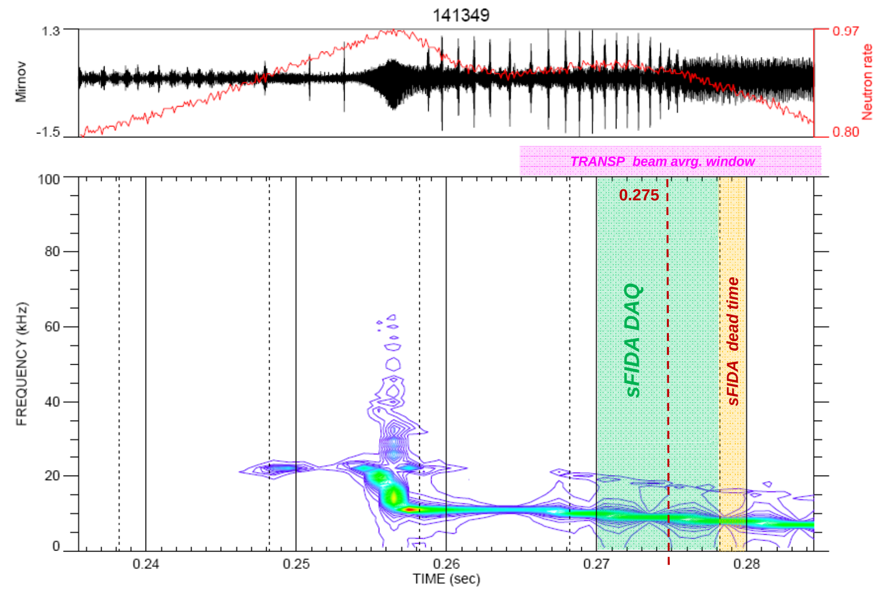
* W.W. Heidbrink, "Fast-ion D_α measurements of the fast-ion distribution", RSI **81**, 10D727, 2010

EPM and kink-like profile flattening example

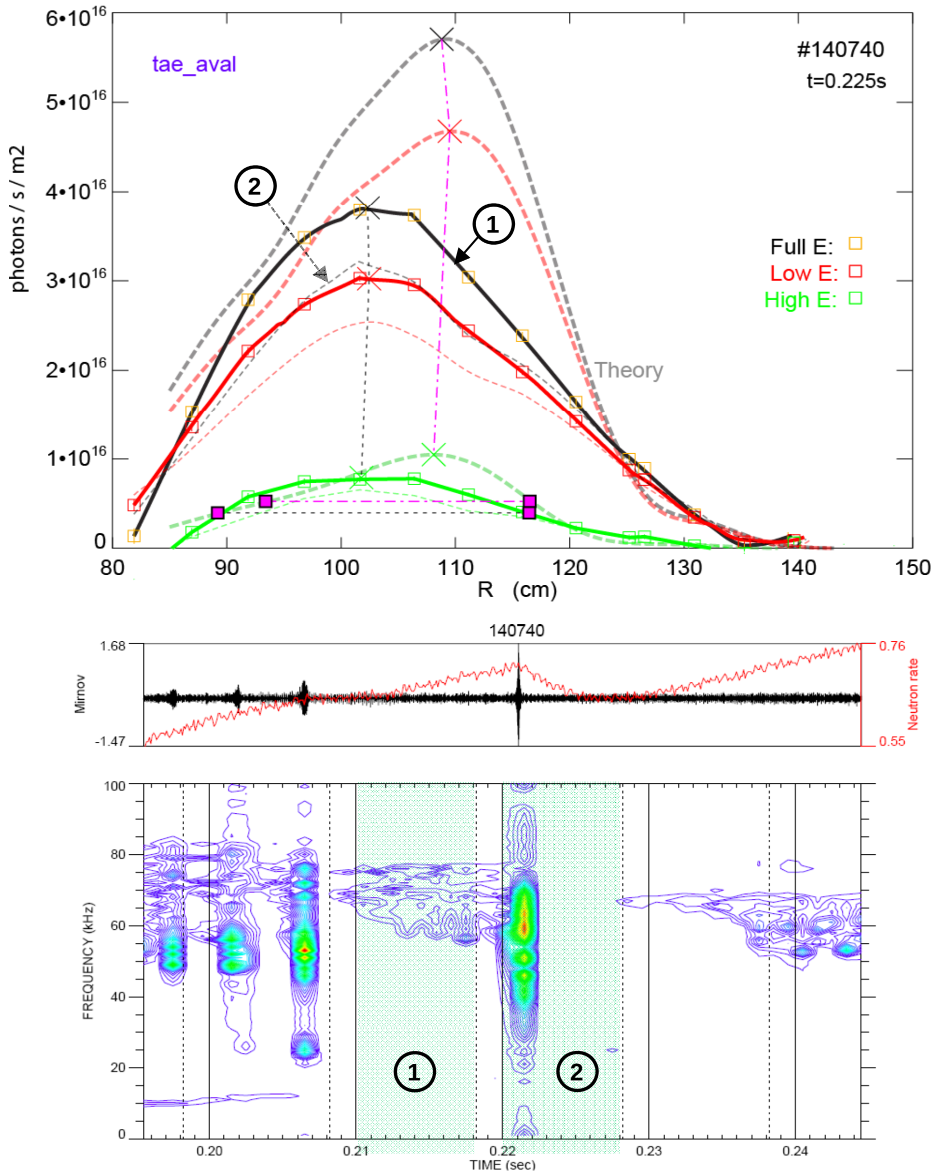


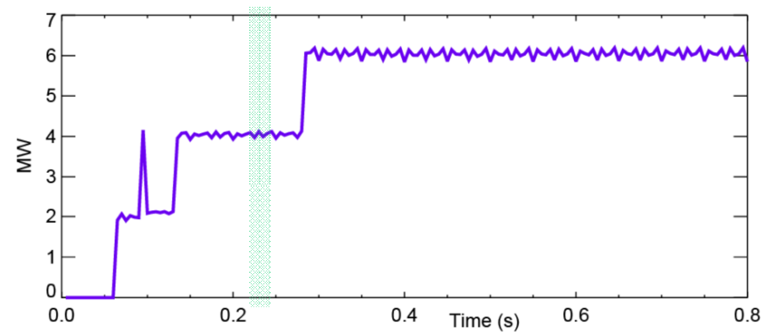






TAE Avalanche: shot 140740, t=0.225s



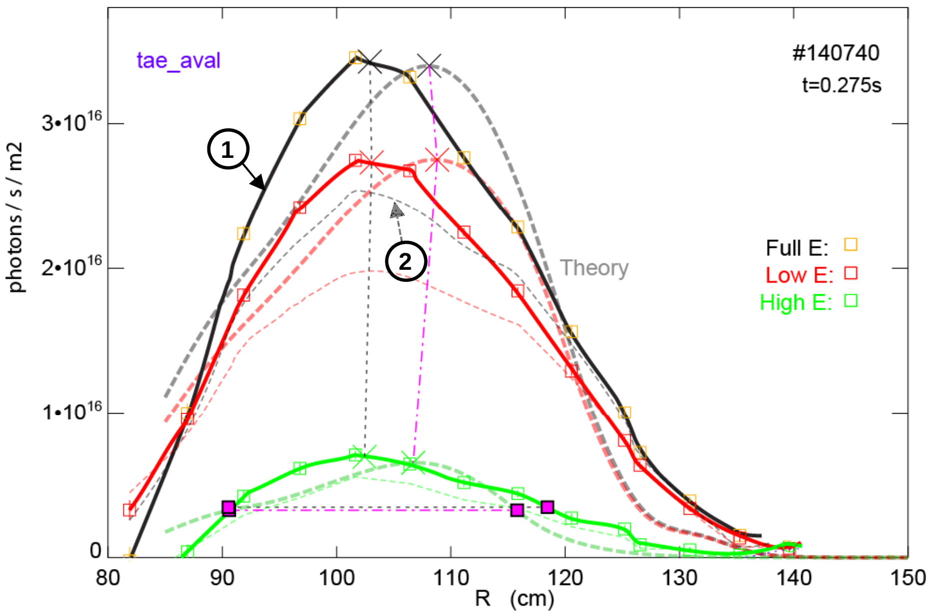


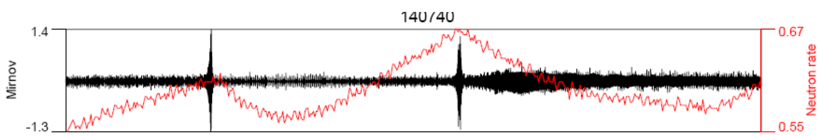
- Good quality s-FIDA data was available for the duration of this shot. Calculated and measured FIDA profiles exhibit features at different times (next 4 slides) usually seen separately in other shots.

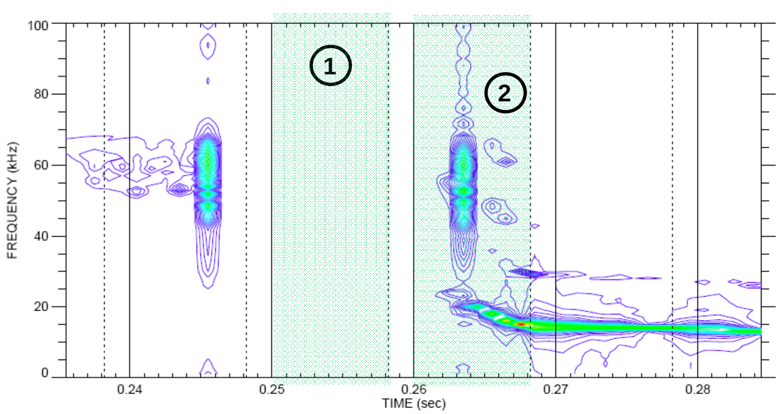
- Beams B and C are active starting at ~0.13s; at 0.28s beam A is added. In the MHD quiet time frame #1 XP profiles have peak values lower by ~40%, are shifted inwards by ~6cm and their FWHM are wider by ~3cm.

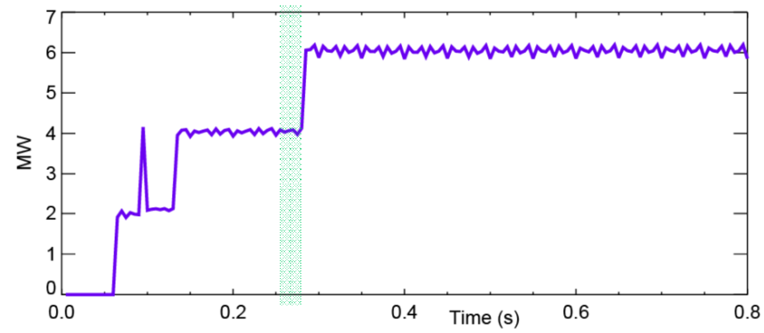
- The TAE avalanche at the beginning of time frame #2 suppresses XP profiles by ~15% and the neutron rate by ~10%. Their shape and peak location do not change.

TAE Avalanche: shot 140740, t=0.275s



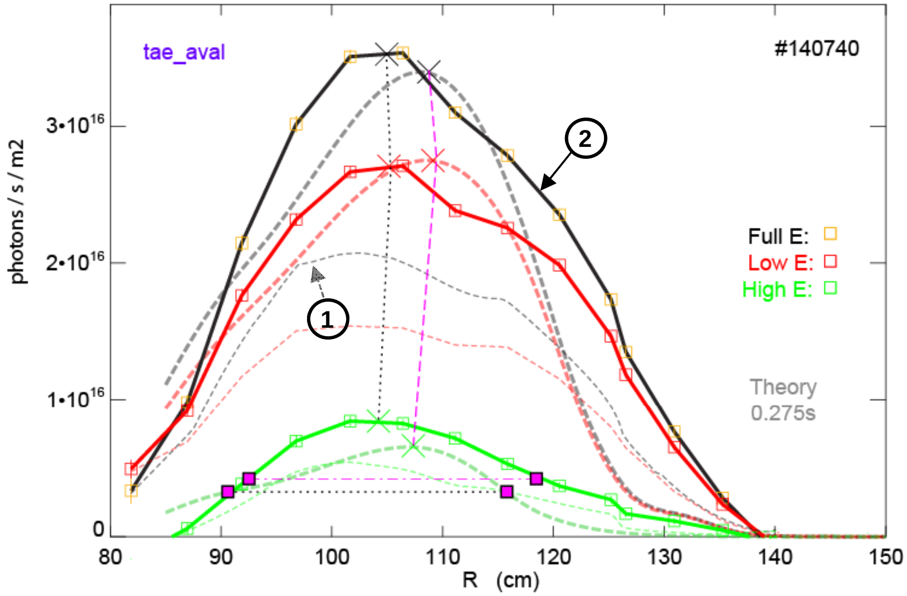


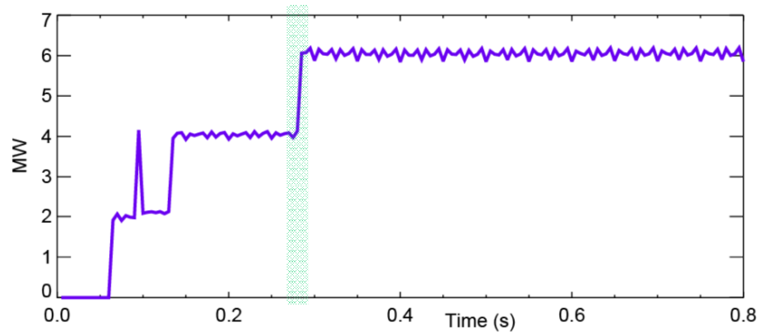


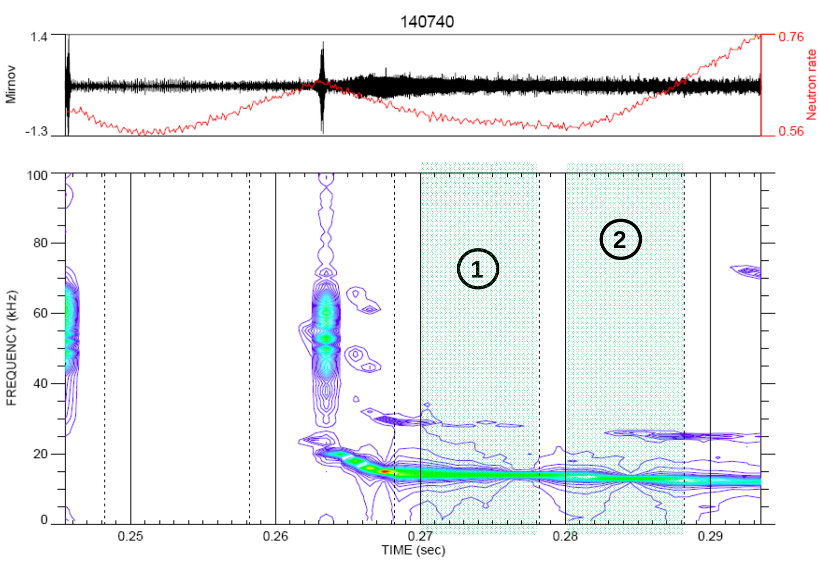


- For the MHD quiet time frame #1 there is very good agreement between measured and calculated profiles. This time frame starts 25ms earlier than t=0.275s, when the theory profiles are calculated, but plasma parameters do not change much over such short times and the two beams have been active for ~100ms.
- The XP profiles are shifted inwards by ~6cm and their FWHM is wider by ~3cm.
- The TAE avalanche in time frame #2 suppresses the measured profiles by ~20% and the neutron rate by ~10%, which continues to drop for an additional ~5% in the next frame.

TAE Avalanche: shot 140740, t=0.27-0.29s





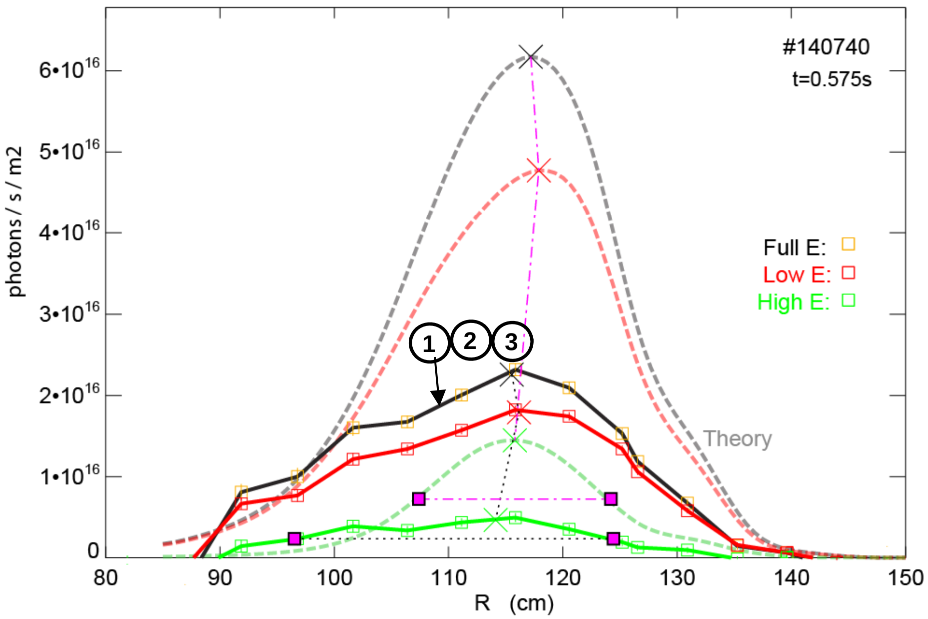


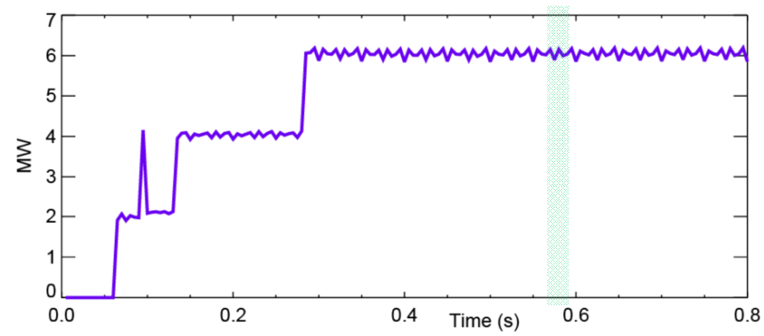
- Here time frame #1, which is just after the TAE avalanche frame but during the kink-like activity, sees further s-FIDA profile suppression. The overall peak value drop with respect to theory profiles at 0.275s is ~40%. All beam energies are affected.

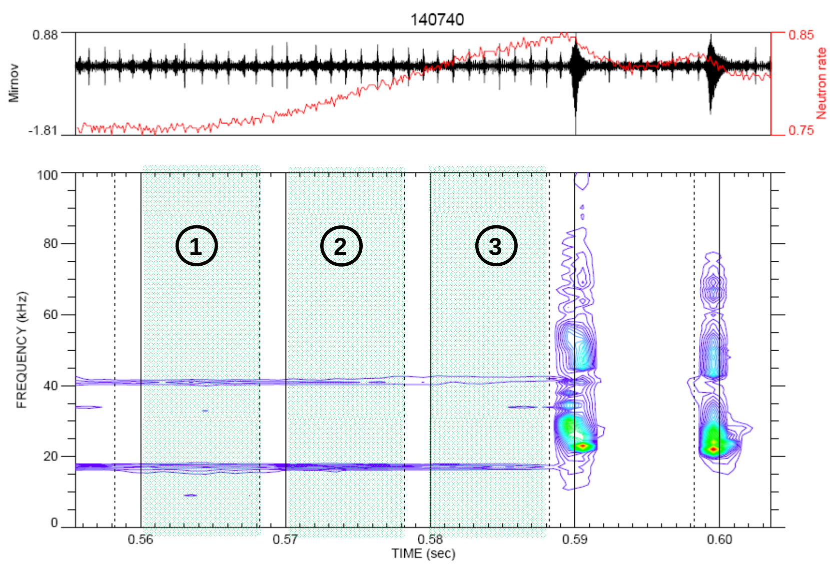
- At 0.28s beam A is added. S-FIDA profiles in time frame #2 register this addition with increase in peak values and widening of the profile on the LFS.

- Avoiding time frames when beam transitions take place simplifies the interpretation of the effect of MHD instabilities on FIDA profiles.

TAE Avalanche: shot 140740, t=0.575s

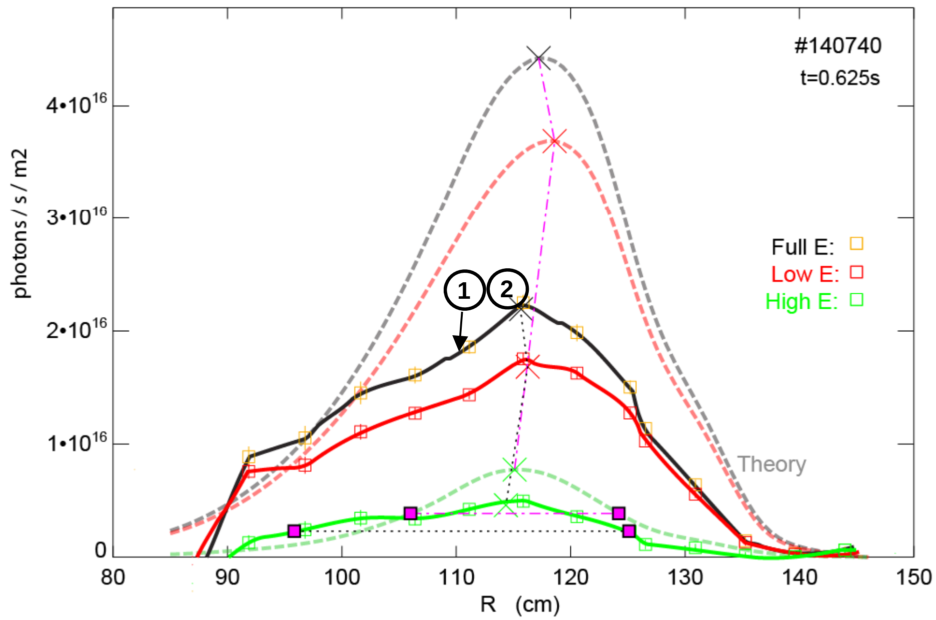


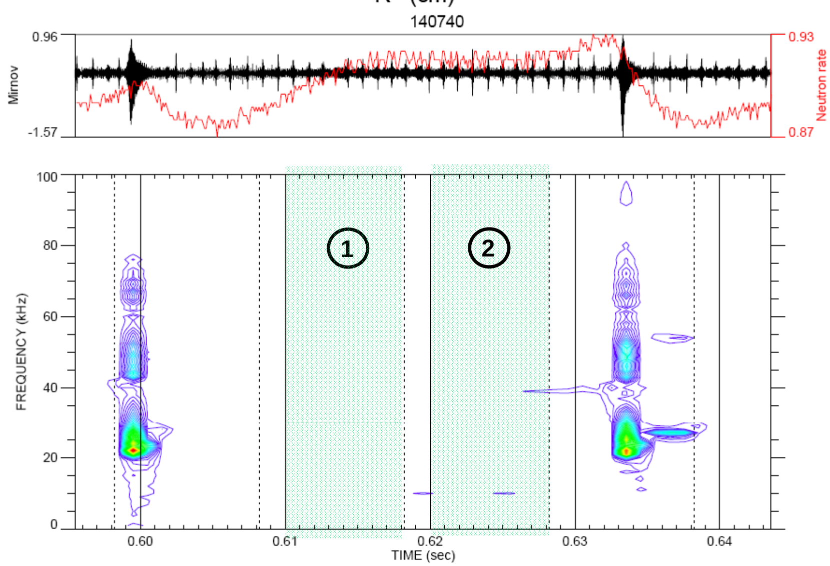


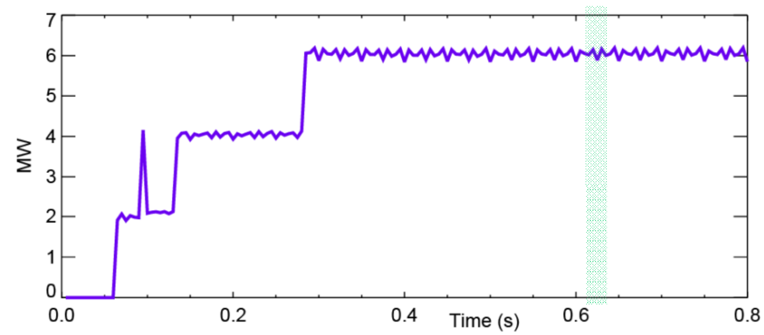


- These 3 time frames have no significant MHD activity resulting in nearly identical experimental FIDA profiles.
- There is a factor of ~3 difference in the peak values between theory and experiment.
- Experimental profiles are substantially wider. The high energy FWHM is ~50% wider.
- All peak locations are well aligned. They are moved further out with respect to the peaks from earlier times due to the larger shafranov shifts.

TAE Avalanche: shot 140740, t=0.625s

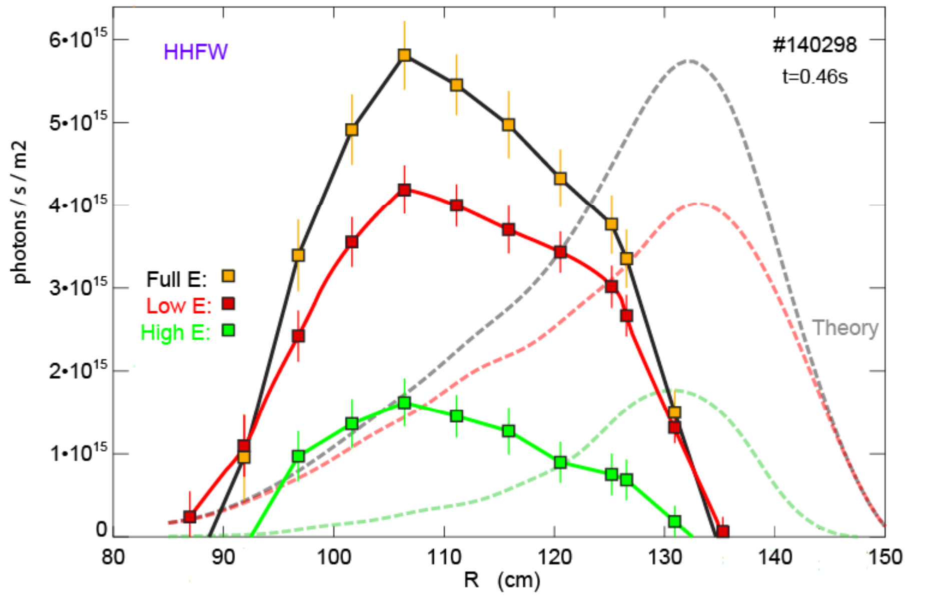


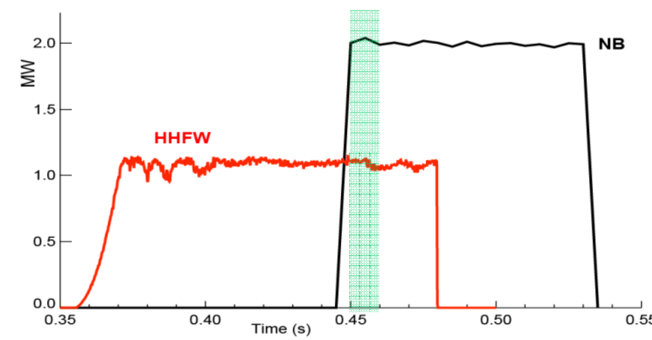


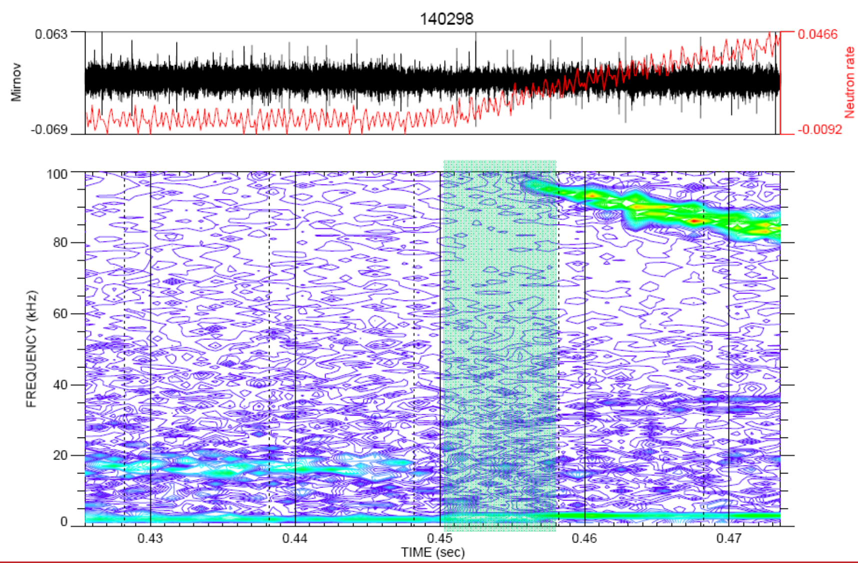


- Another confirmation that for time frames with no significant MHD activity s-FIDA measures nearly identical profiles.
- The peak value difference between theory and experiment dropped from a factor of ~3 to ~2.
- Experimental profiles are still substantially wider.
- All peak locations are aligned within 2-3 cm .

Example: HHFW shot 140298, t=0.46s

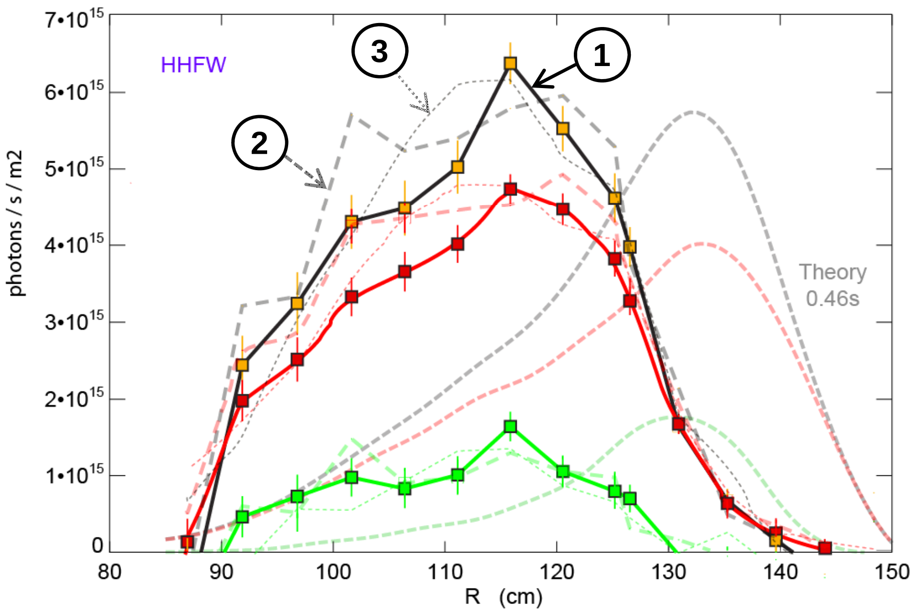


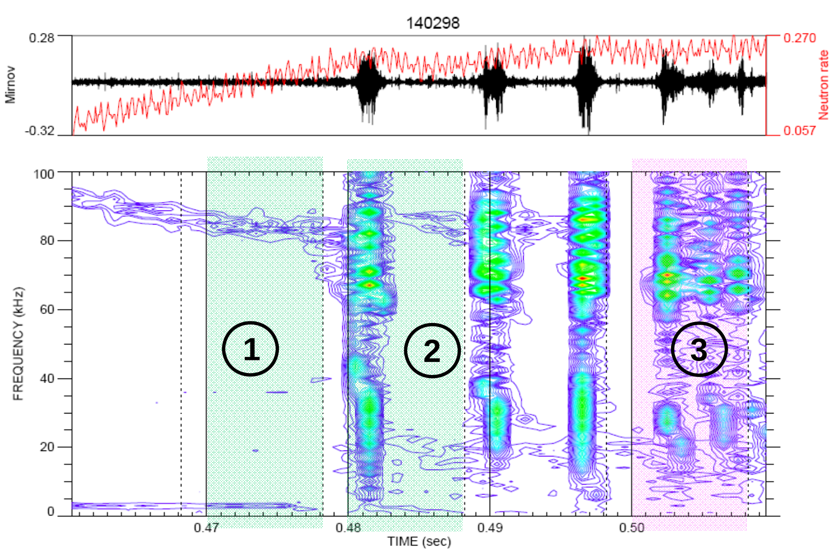


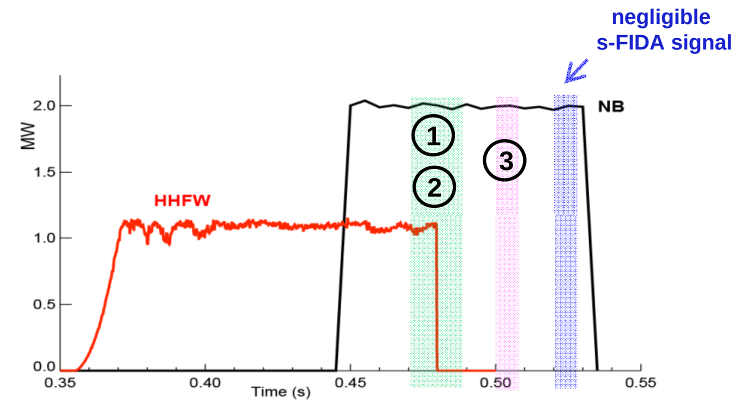


- Here FIDASIM calculates strongly outward shifted (~30cm) profiles
- Peak values are similar but profile shapes are very different
- This plasma is heated by 1.1MW HHFW and probed with a single short 2MW beam pulse. It is relatively MHD quiet.
- Can this case help explain the mystery of outward shifted theory profiles with peak values often a factor of 2-3 higher than the experiment ?
- Note: TRANSP neglects HHFW acceleration of beam ions.

Example: HHFW shot 140298, t=0.47-0.51s







- Peak values in time frames 1-2-3 are similar to calculated peak values at 0.46s.
- The last 10ms of the beam pulse do not create any appreciable s-FIDA signal. HHFW has been turned off for 40ms by this time.
- However, timeframe #3, 20ms after HHFW has been turned off, has appreciable signal. The experimental FIDA profiles for #1 and #3 are similar. #2 has broader profile perhaps due to the MHD activity at 0.49s acting on larger beam ion population.
- These observations suggest acceleration of beam ions by HHFW in this plasma.

Discussion

- There are cases when FIDA profiles from theory and experiment agree well. However, even for MHD quiet instances theory profile peaks are 2-3 times higher. Experimental profiles are often shifted inwards, sometimes by over 10cm. Although beam ion loss and redistribution are expected to have similar effect on the profiles we believe they can not explain the magnitude of the observed discrepancies.
- Possible causes due to code errors related to geometry or direction of toroidal magnetic field were eliminated.
- The uncertainty of the neutral gas density in TRANSP simulations has small effect on the FIDASIM profiles.
- The TFTR beams which operate at max 90kV in NSTX may have somewhat different full, half and third energy fractions. This possibility and others are currently under investigation.

Conclusions

- A new database with ~350 shot and time cases (previously identified as having ALE/EPM/TAE activity) is populated with numerous parameters attempting to quantify the deviation of measured from calculated FIDA spectra and resulting profiles. The larger this deviation is, the larger the instability effect on beam ion confinement should be.
- Examples of profile suppression, broadening and flattening due to beam ion instabilities are shown.
- Measured FIDA profiles in a HHFW heated shot may indicate beam ion acceleration by HHFW.
- This work suggests that careful reevaluation of the selected times, and possibly instability classifications, is needed. The magnetics data should guide the time selection and the s-FIDA data acquisition window should preferably include the onset of the instability.