Recent Fast-Ion D-Alpha (FIDA) Analysis

- FIDA* diagnostic
- Simulation code
- Quiet plasmas
- Ion cyclotron acceleration
- Alfven eigenmode transport

W. Heidbrink, Y.Luo, K. Burrell, E. Ruskov, W. Solomon, M. Van Zeeland, N. Gorelenkov, R. White et al.

Heidbrink, PPCF **46 (2004) 1855;*

*Luo, RSI **78** (2007) 033505.*

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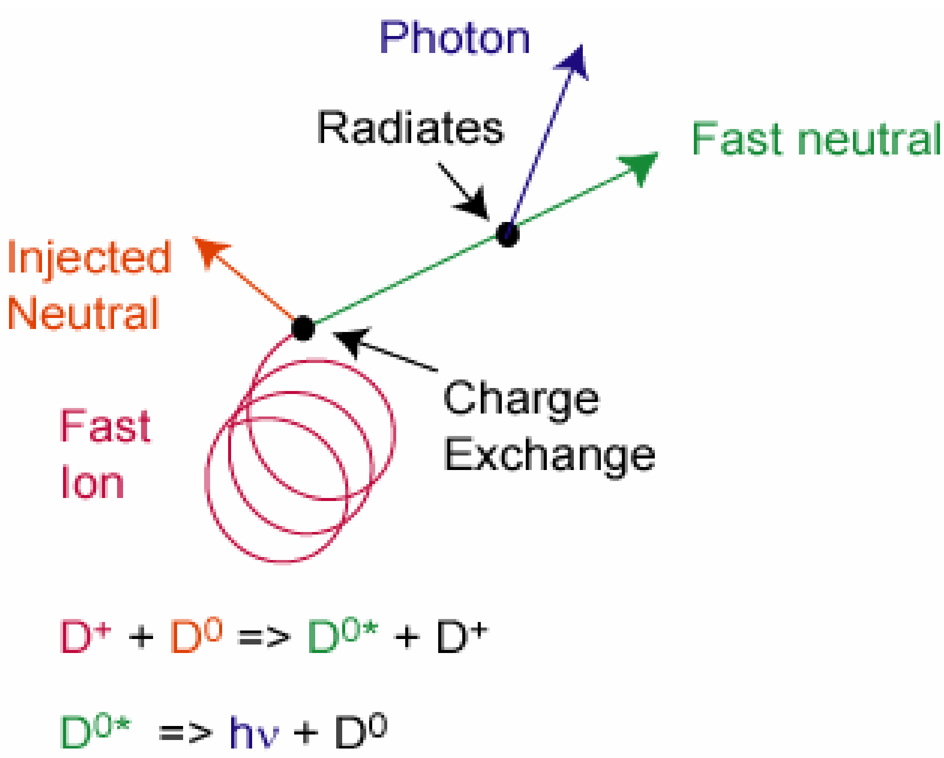
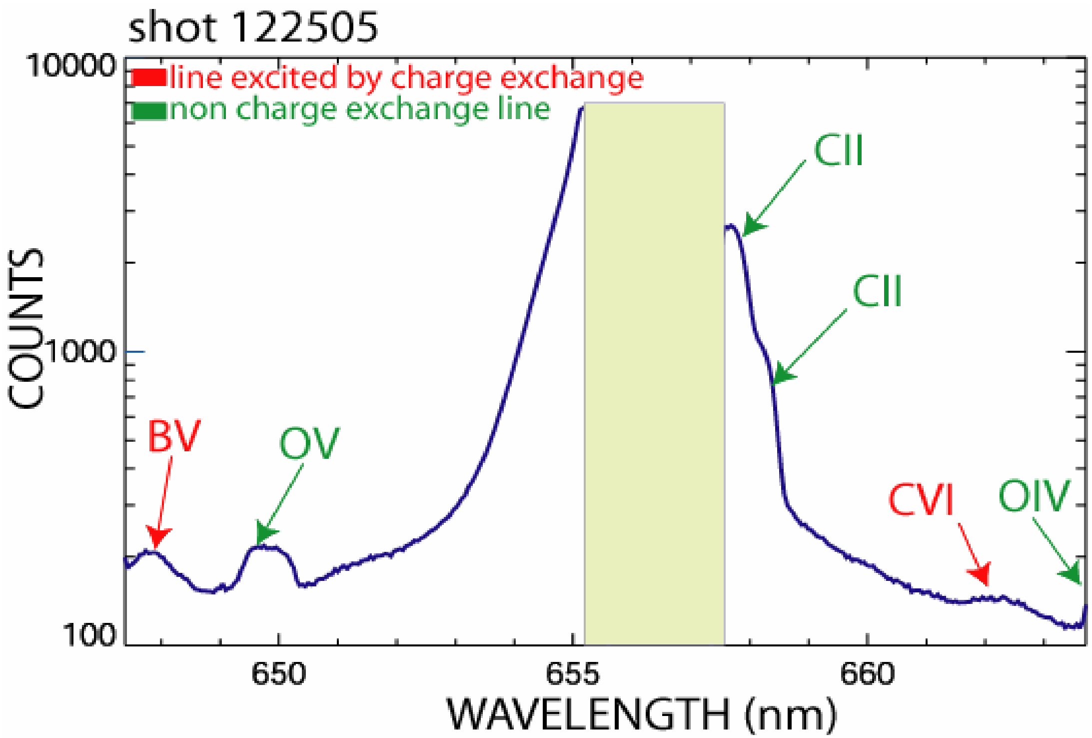
D_α light from neutralized fast ions



- Charge exchange light $S_{FIDA} \propto n_b n_f \langle \sigma v_{rel} \rangle$
- Wavelength determined primarily by Doppler shift. One velocity component measured.
- Cross section depends on relative velocity. Spectral shape distorted.

Care is needed in extracting the fast-ion feature



- Very bright cold D-alpha line
- Bright injected neutral feature
- Impurity lines

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Background Subtraction Normally Determines the Signal:Noise

$T = F + V + I_{cx} + I_{ncx} + S_{cold} + S_{inj}$ (red only appears w/ beam)

T = Total signal

F = Fast-ion signal (the desired quantity)

V = Visible bremsstrahlung

I_{cx} = Impurity charge-exchange lines

I_{ncx} = Impurity non-charge-exchange lines

S_{cold} = Scattered Dalpha from edge neutrals

S_{inj} = Scattered Dalpha from injected & halo neutrals

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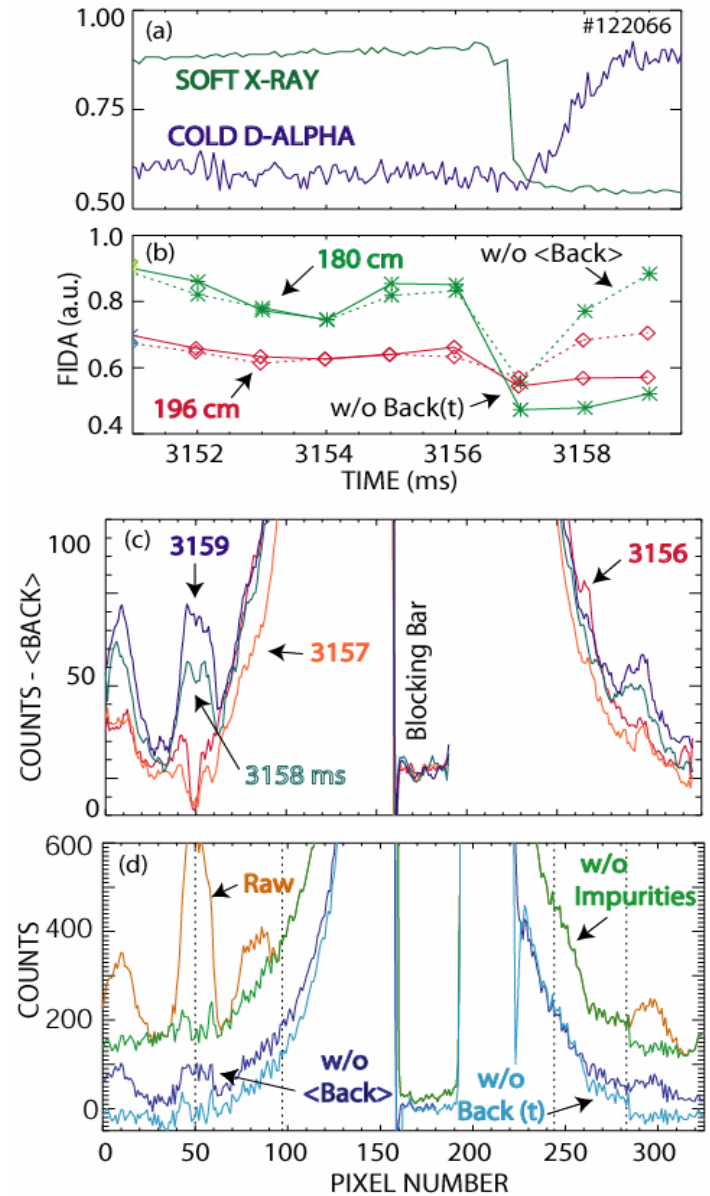
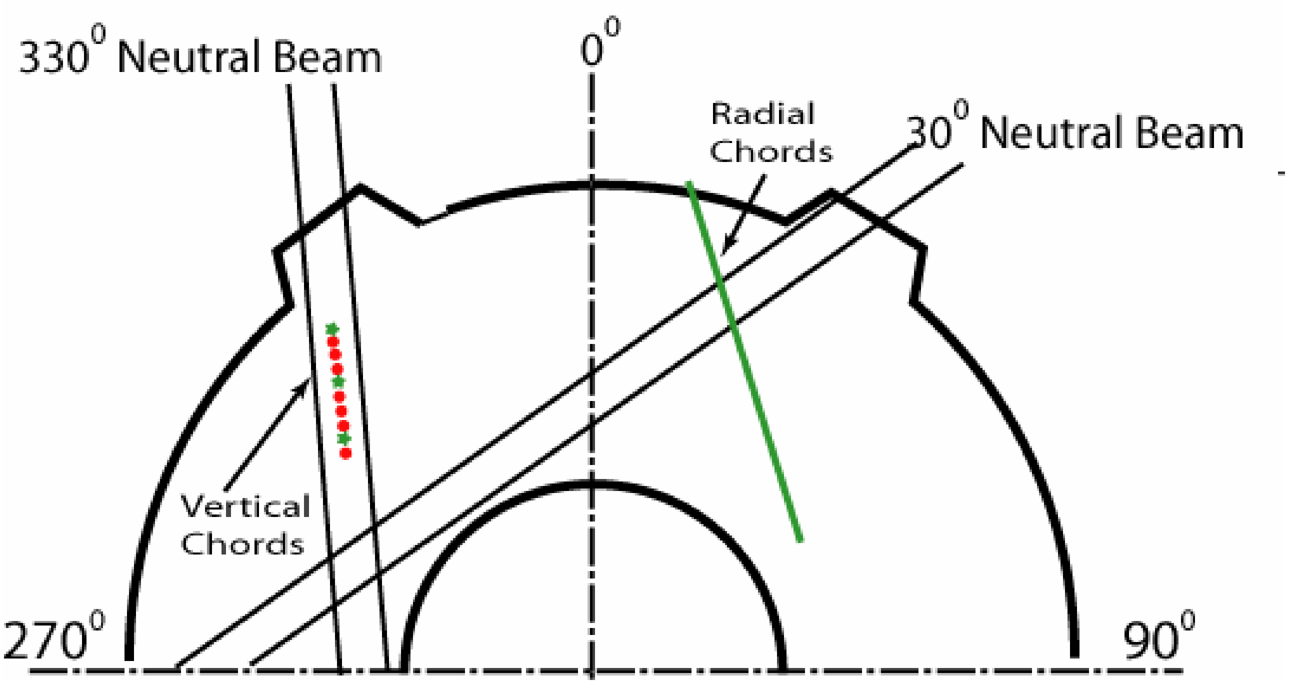
Current approach: Use beam modulation to subtract black terms; eliminate I_{cx} by fitting

Scattered D-alpha Contaminates Signal & Changes in Time

- Instabilities expel particles & heat to edge → background light changes
- Cold Dalpha light appears in all pixels

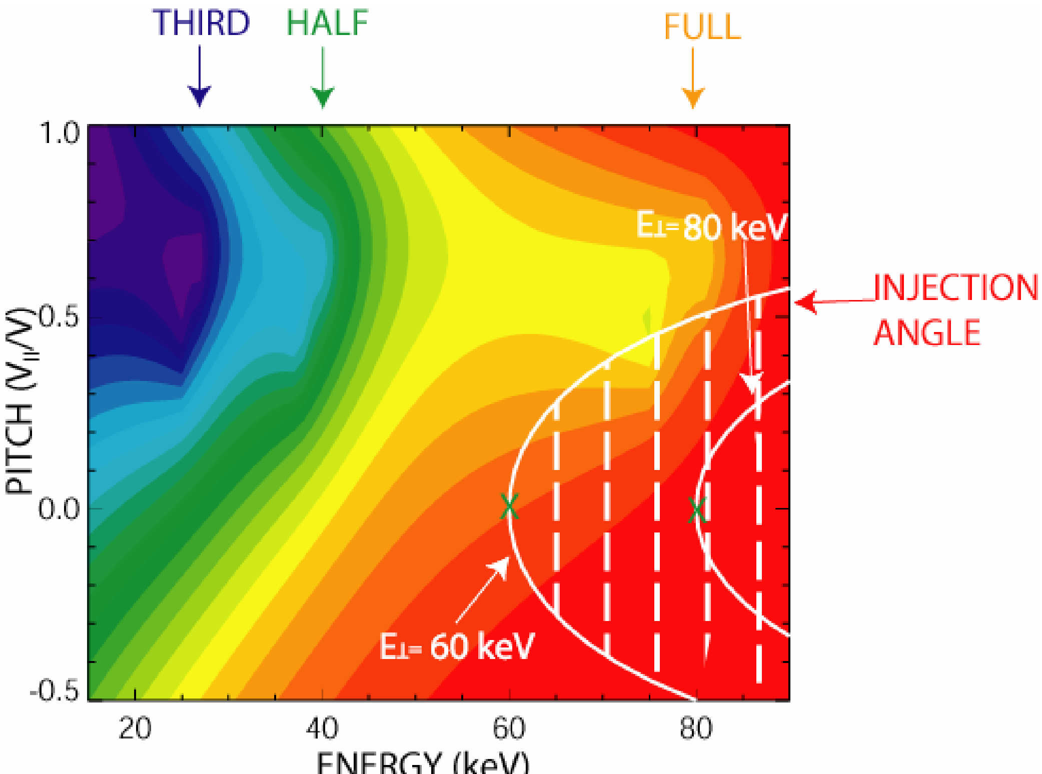


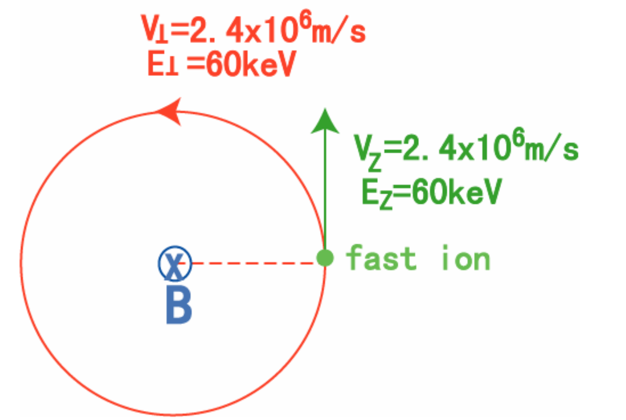
FIDA fiber views during the 2005 Campaign

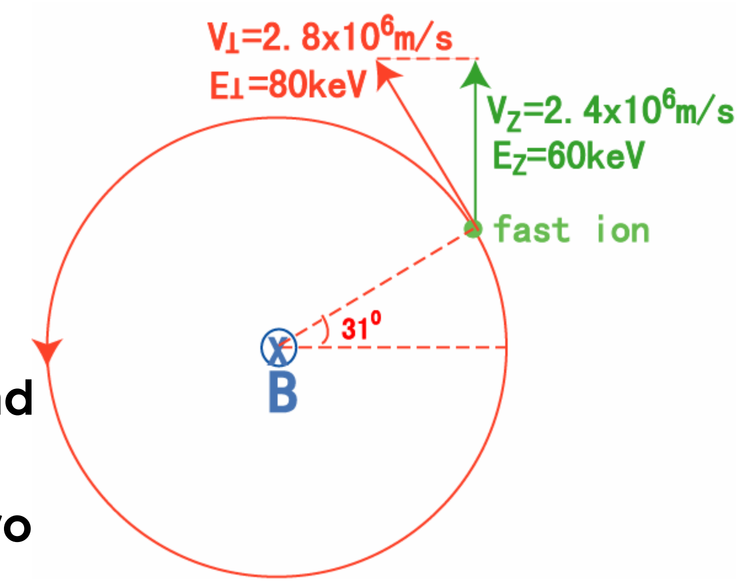


- Dedicated 2-channel system measured full spectra
- Partial spectra from 7 vertical channels on selected discharges
- Used radial views to study viewing angle dependence

Spectra measure one velocity component : Signal is a weighted average in velocity space







- $\lambda \rightarrow E_z \rightarrow$ perpendicular energy
- A curve with constant perpendicular energy and enclosed area contribute to a particular λ
- Overall weight of each fast ion is product of gyro phase weight and atomic cross section weight

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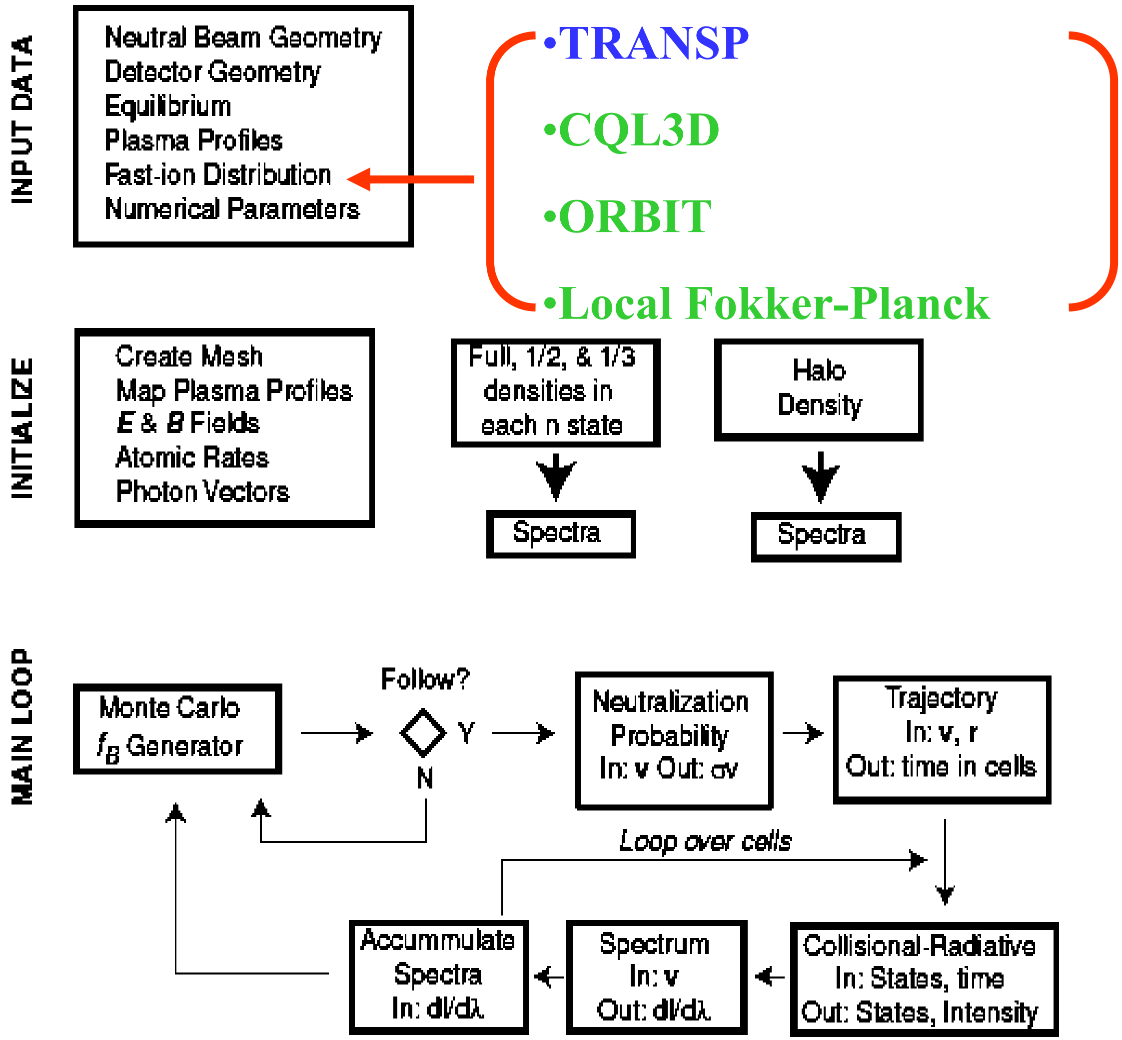
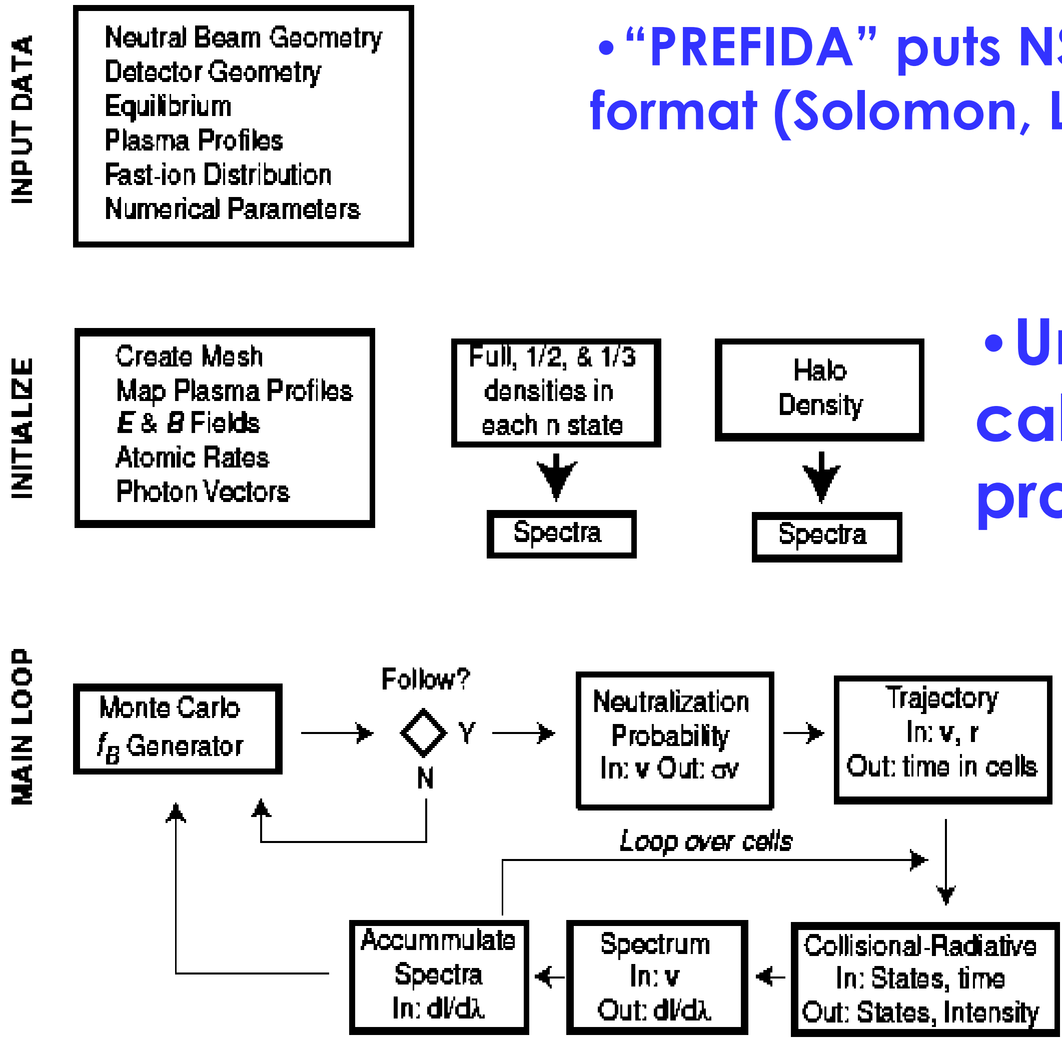
Weighted Monte Carlo code simulates expected signal

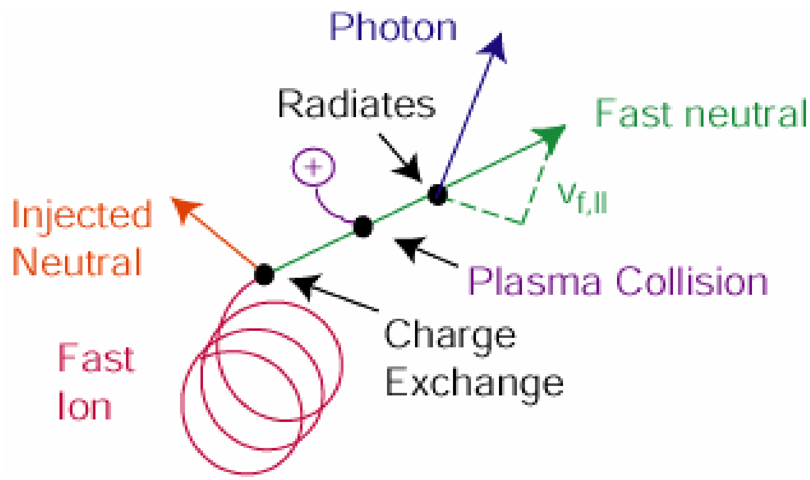


We're preparing this FIDA/NPA simulation code for NSTX



- "PREFIDA" puts NSTX data into standard format (Solomon, Liu)
- Unlike TRANSP, code calculates halo density properly
- Deyong is writing a version that computes the NPA signal

Use Simulation Code to Investigate the Sensitivity to Experimental Errors



- Atomic physics of charge exchange and collisional radiative balance
- Neutral density
- Fast-ion distribution function

- *Emil Ruskov performed this study*
- *n_e, T_e, T_i, and Z_{eff} varied*

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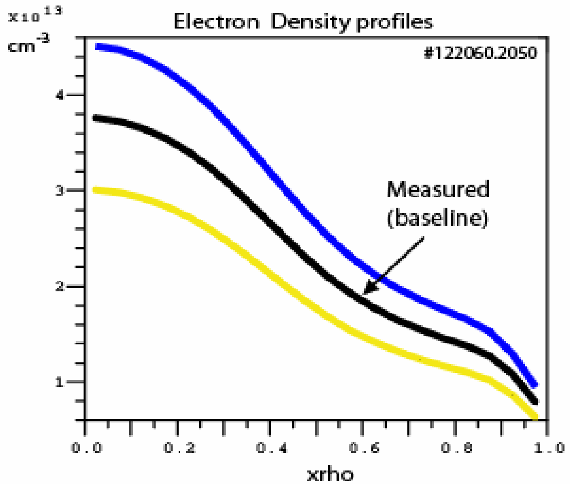
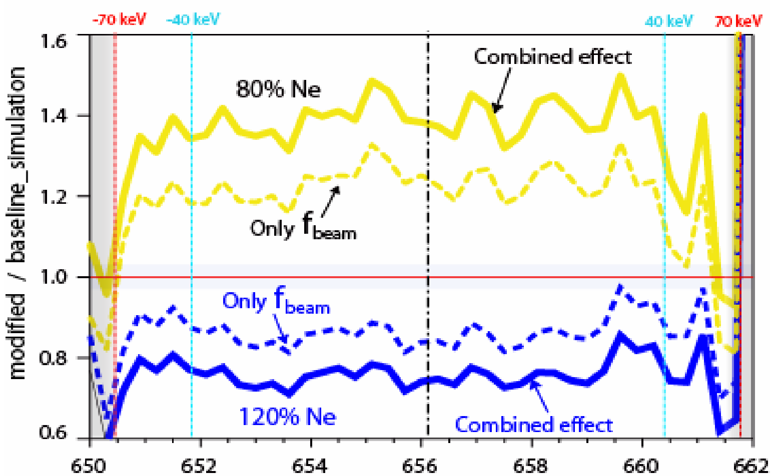
Uncertainties in Electron Density Have Largest Effect on Simulated Signals





Inferred Fast-Ion Density

- Weak sensitivity of atomic processes
- Neutral density depends on n_e through beam deposition
- T_i , Z_{eff} , T_e unimportant
- Typically 8% uncertainty

Comparison with Theory

- Strong n_e & T_e dependencies through slowing-down time
- T_e & Z_{eff} affect high energies through pitch-angle scattering
- Typically 20% uncertainty

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Quiet Plasma Study by Yadong Luo

Intensity calibration allows direct magnitude comparison

- Simulation gives the number of photons collected by the lens
- FIDA measurement gives the number of digitizer counts from the CCD camera
- Intensity calibration tells the conversion factor from photons to digitizer counts

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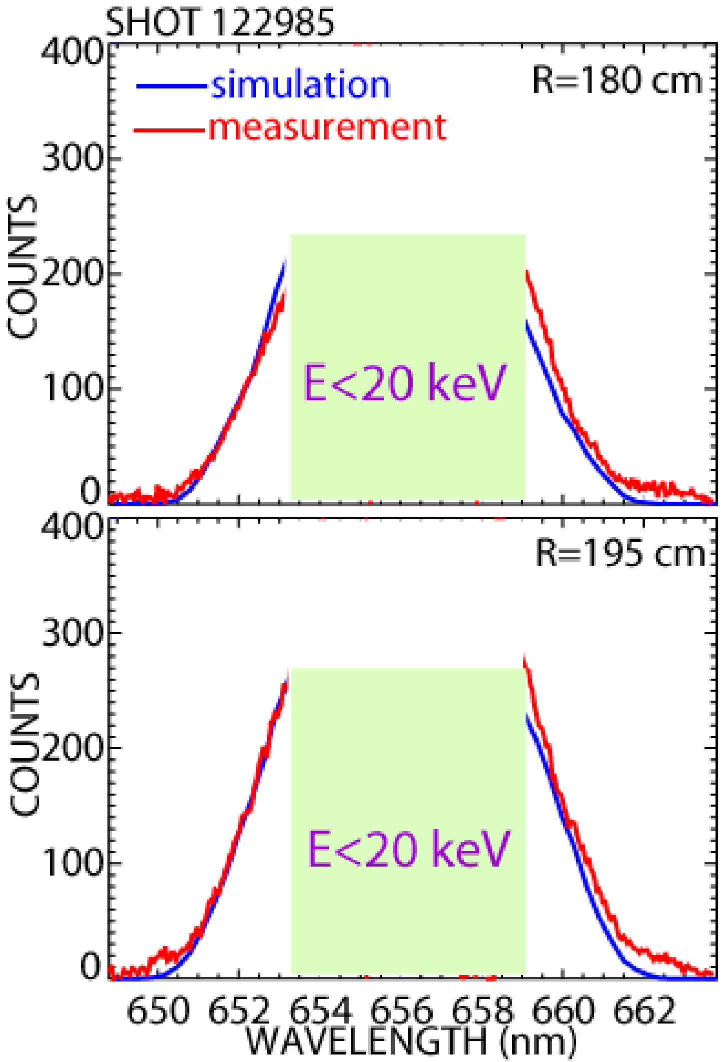
Both magnitude and shape of spectra agree well



- For the 180 cm chord, simulated spectrum are scaled by 0.75 to get the agreement. 20-30% magnitude difference is reasonable provided errors in data processing, intensity calibration, plasma profiles input to TRANSP and the simulation code, etc.
- Excellent shape agreement validates TRANSP fast-ion velocity space model and atomic cross sections in the simulation code.
- The result benchmarks both the simulation code and the diagnostic.

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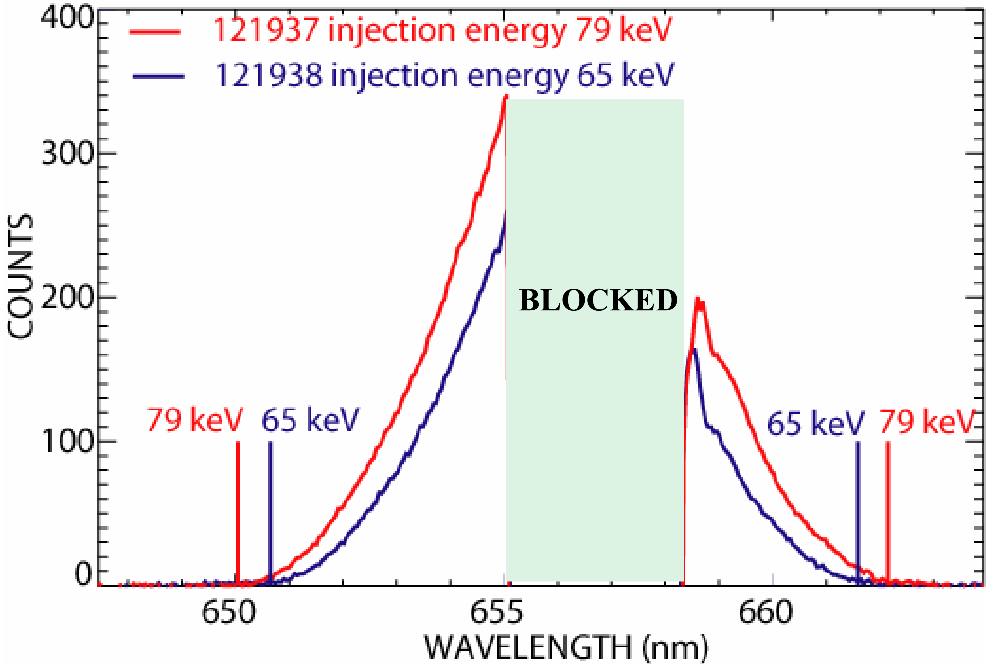
Classical theory of fast ions

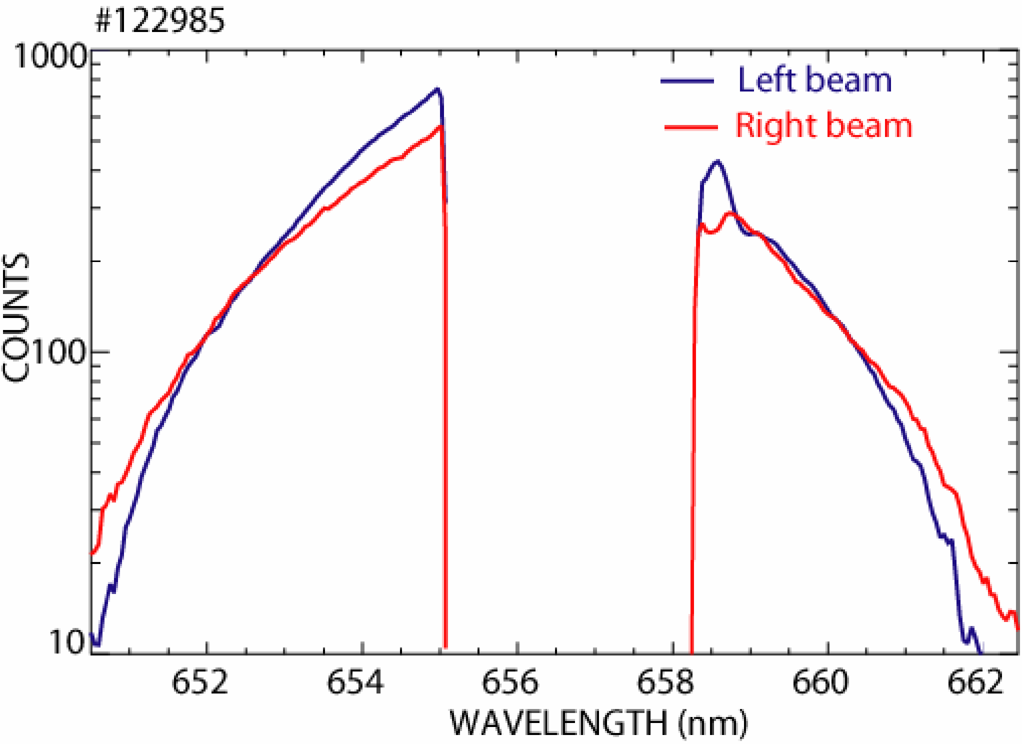
- Fast ions are born with an initial energy and pitch by neutral beam injection
- Fast ions slow down through Coulomb collisions with electrons and thermal ions
- Fast ions pitch angle scatter through Coulomb collisions with thermal ions
- Fast-ion density is proportional to the product of the beam power and the slowing down time, which is $P_{inj}f(T_e)/n_e$

Detected fast ions have the maximum energy of injection energy



- The highest energy which fast ions can have without RF heating is approximately the injection energy
- FIDA signal is at zero above the injection energy and the transition point is at the injection energy
- The transition point moves as expected when the injection energy changes

More signal detected in the high energy range with perpendicular injection



- Fast ions are born with a larger initial pitch angle with right beam injection
- More fast ions have a high perpendicular energy because less pitch angle scattering is required
- All the other parameters are kept constant
- Signal is stronger with right beam injection in the high energy range as expected

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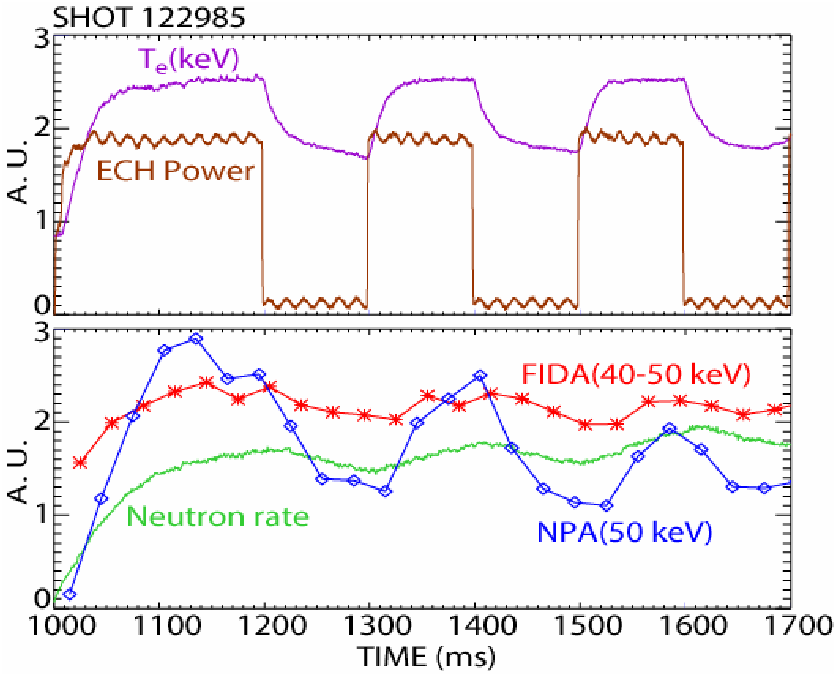
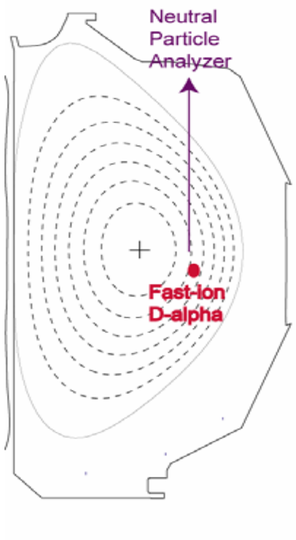
FIDA signal is less sensitive to pitch-angle scattering than neutral particle analyzer signal





- The FIDA signal increases with T_e because of the longer slowing down time (higher fast-ion density) and more pitch angle scattering (more perpendicular energy)
- The FIDA signal is less sensitive because FIDA measures a collection of fast ions in velocity space, while NPA measures a point in velocity space. (Neutrons also average in velocity space.)

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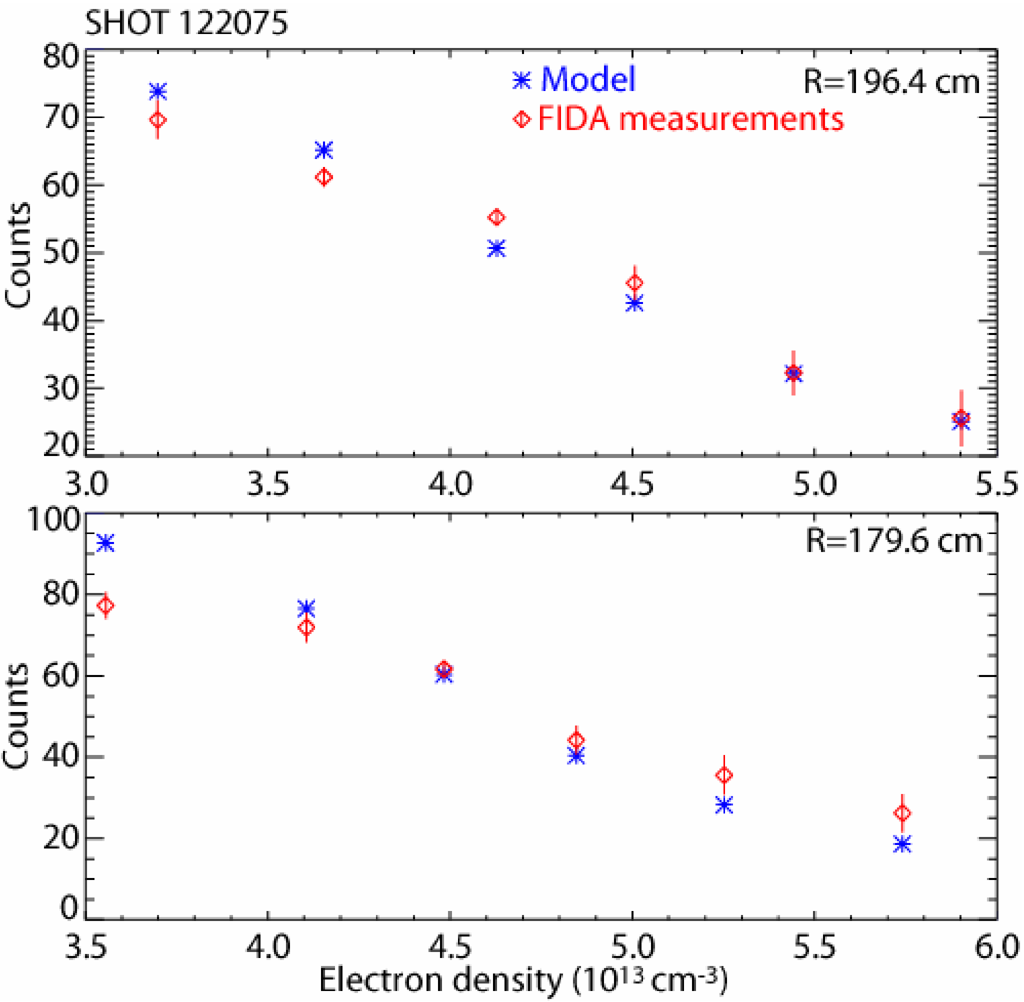
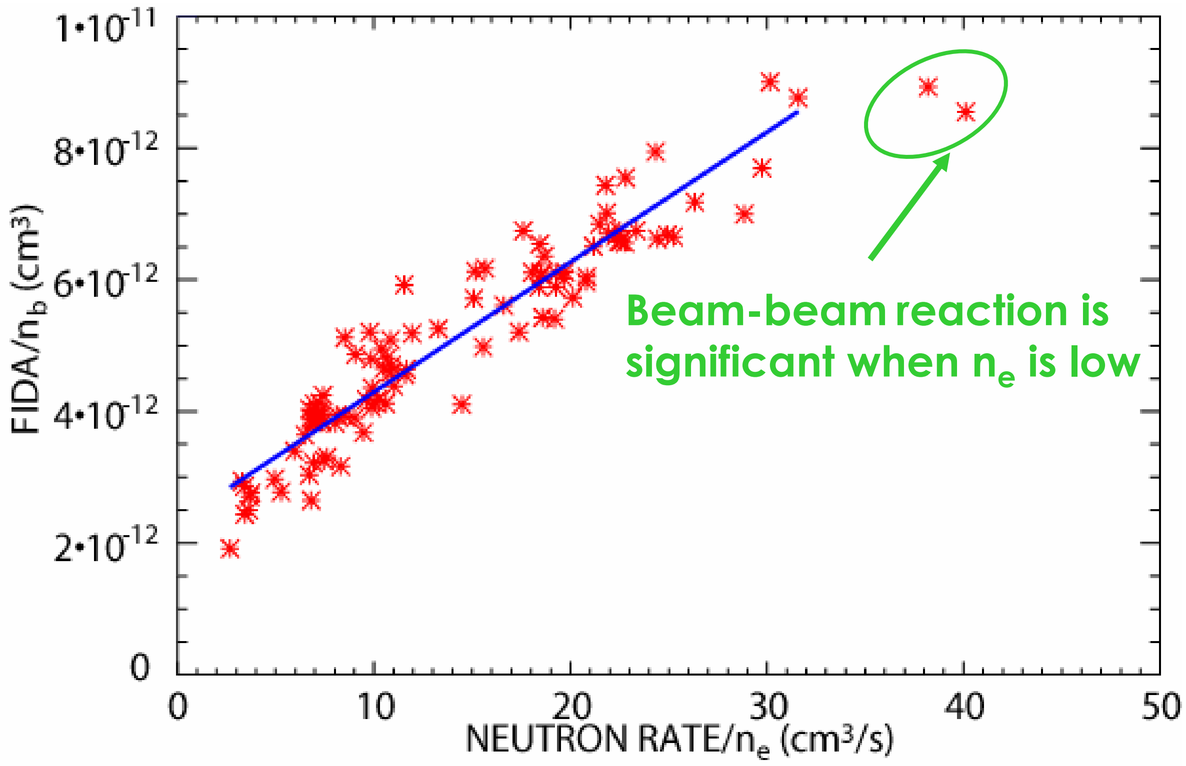
The FIDA Signal Decreases with Increasing Density



- FIDA signal decreases with ne increasing because of shorter slowing down time (lower fast-ion density)
- All atomics physics neglected, which is legitimate when the velocity distribution doesn't change and only signal level is concerned. One free parameter in the model.
- Good agreement between the FIDA measurements and the simple model.

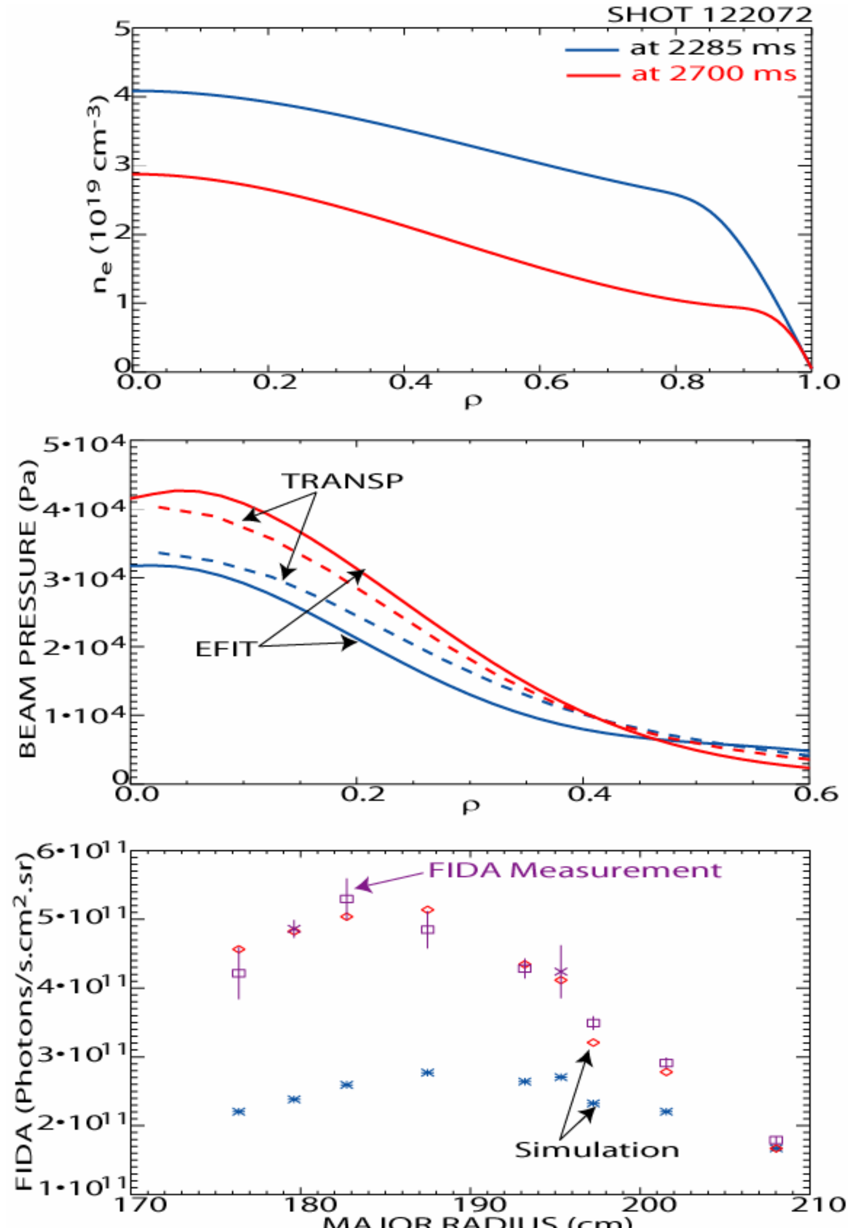
Neutron diagnostic corroborates FIDA measurements



- Neutron rate/n_e is proportional to fast-ion density if beam-thermal nuclear reaction dominates
- A linear relationship is observed

FIDA relative radial profile agrees well with TRANSP prediction

- Fast-ion distributions from TRANSP are dumped to the simulation code
- Simulated profiles are higher as expected at the later time when electron density is lower
- At the early time, FIDA profile is normalized to the simulated profile
- At the later time, FIDA profile agrees with the simulated profile
- Radial profile of fast-ion pressure inferred from kinetic EFITs (MSE data) are also consistent with TRANSP



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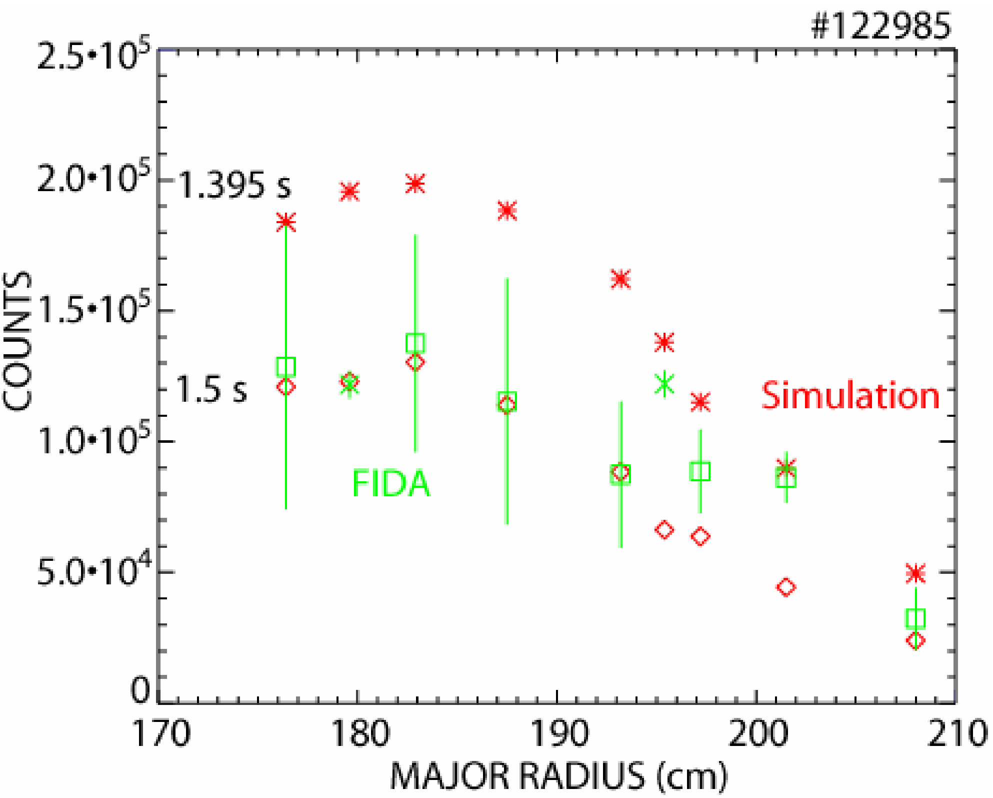
First Try at Radial Profile in Quiet Plasma showed Disagreement



- This one-source L-mode plasma has modest Alfven activity!
- The EFIT fast-ion pressure profile differs from TRANSP as well

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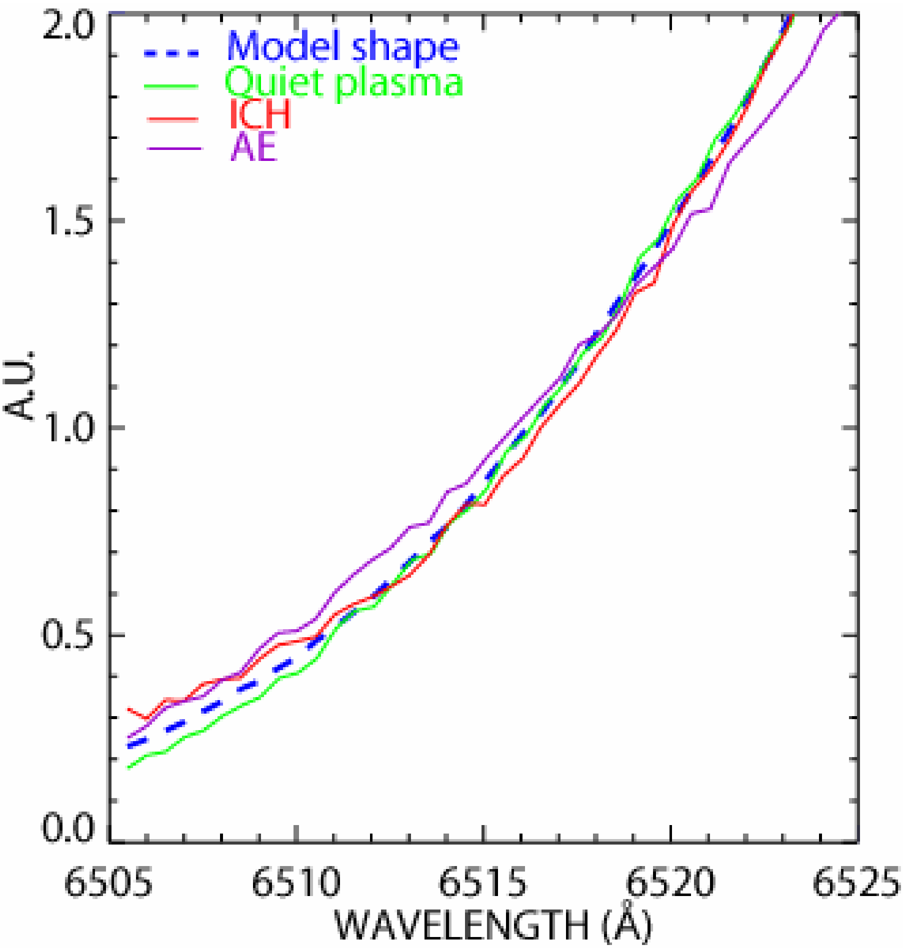
Spectral shape informative on velocity space



- **Model shape is the average of several spectra with quiet plasmas.**
- **The quiet plasma case: T_e=1.1 Kev. Less pitch angle scattering.**
- **The ICH case: high energy fast ions are accelerated.**
- **The AE case: Fast ions from the core region are expelled.**
- **Database results: reduced chi squares 0.33, 0.44, 0.50 respectively.**

Velocity distribution is usually determined by Coulomb collisions, but can be altered by ICH and instabilities

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Conclusions of Quiet Plasma Study

Velocity space (spectrum)

- Excellent spectral shape agreement
- Expected injection energy dependence
- Expected injection angle dependence
- Expected viewing angle dependence
- Deviations from normal spectral shape informative

Number of fast ions (intensity)

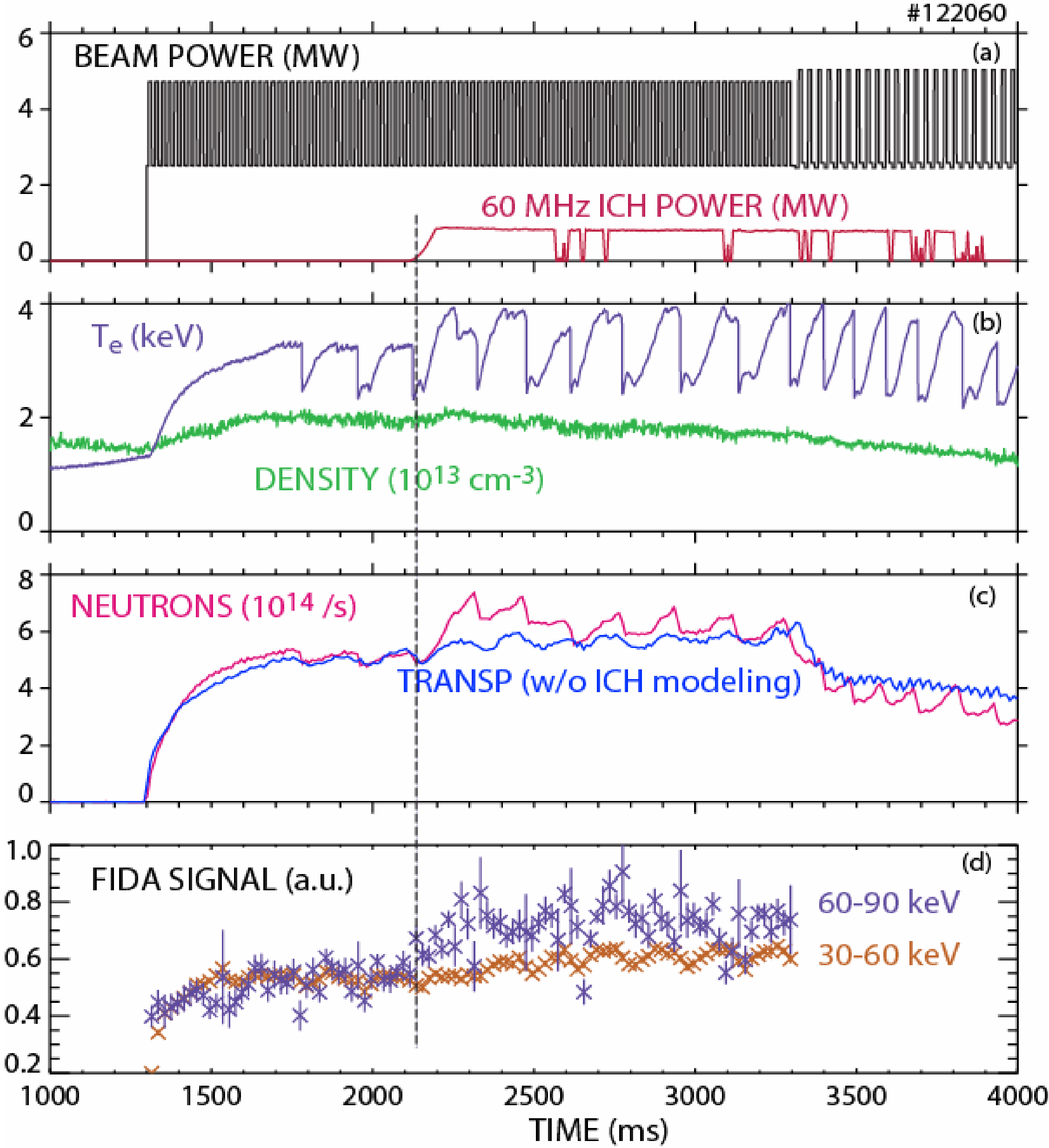
- Good spectral magnitude agreement
- Expected beam power dependence
- Expected electron density dependence
- Expected electron temperature dependence
- Corroborated by neutrons

Radial transport (profile)

- Good relative profile agreement
- Poor agreement on absolute profile

Perpendicular Fast-ion Acceleration at 4th Cyclotron Harmonic

- Neutron enhancement during ICH → fast-ion acceleration
- FIDA data → distribution function distorts
- Slight increase in bulk; perpendicular tail forms
- Error bars show random errors (dominated by background subtraction)



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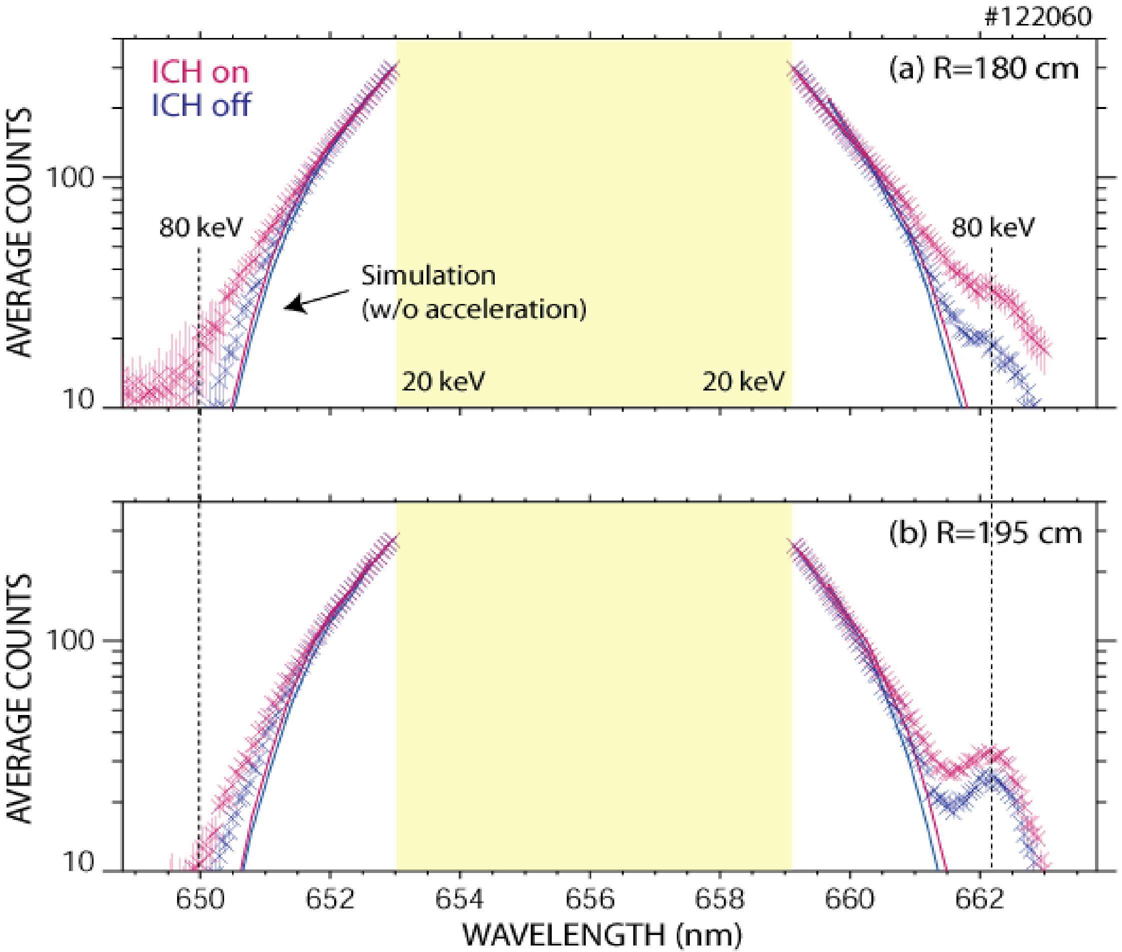
FIDA Spectrum Distorts due to 4th Harmonic Heating



- Distortion occurs above ~ 50 keV (Harmonic heating is expected to affect high energy ions most)
- Tail is larger for FIDA channel that is closest to the resonance layer

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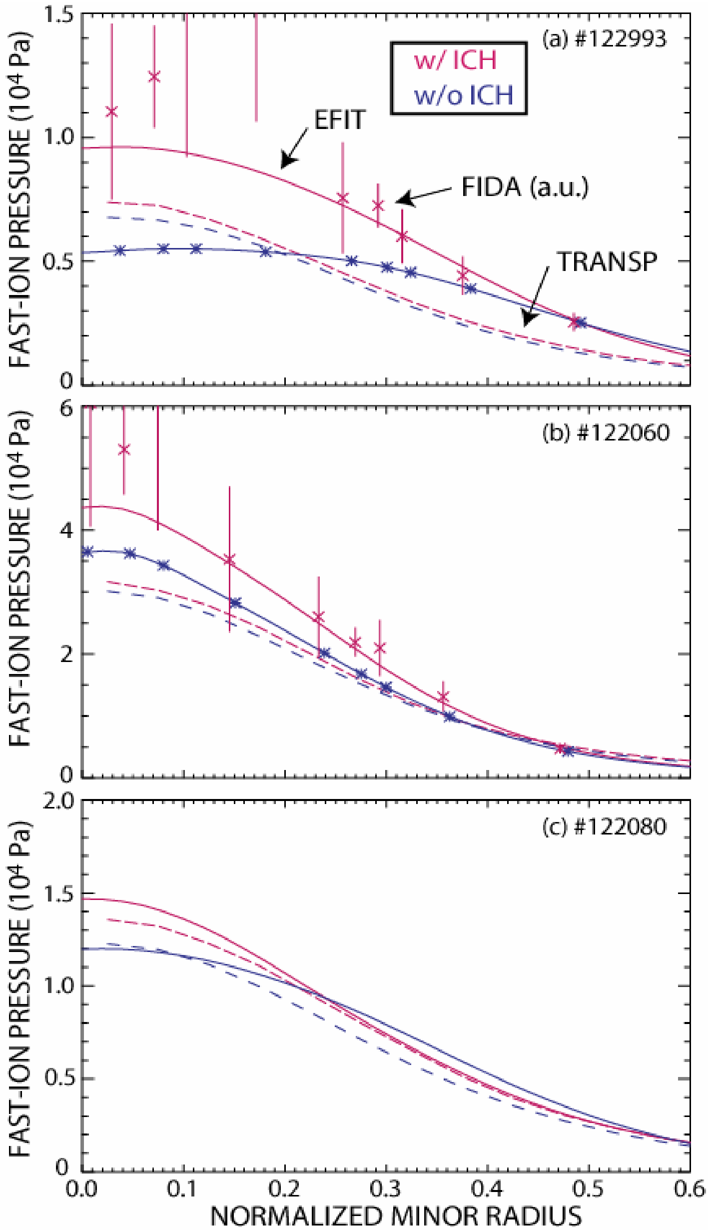
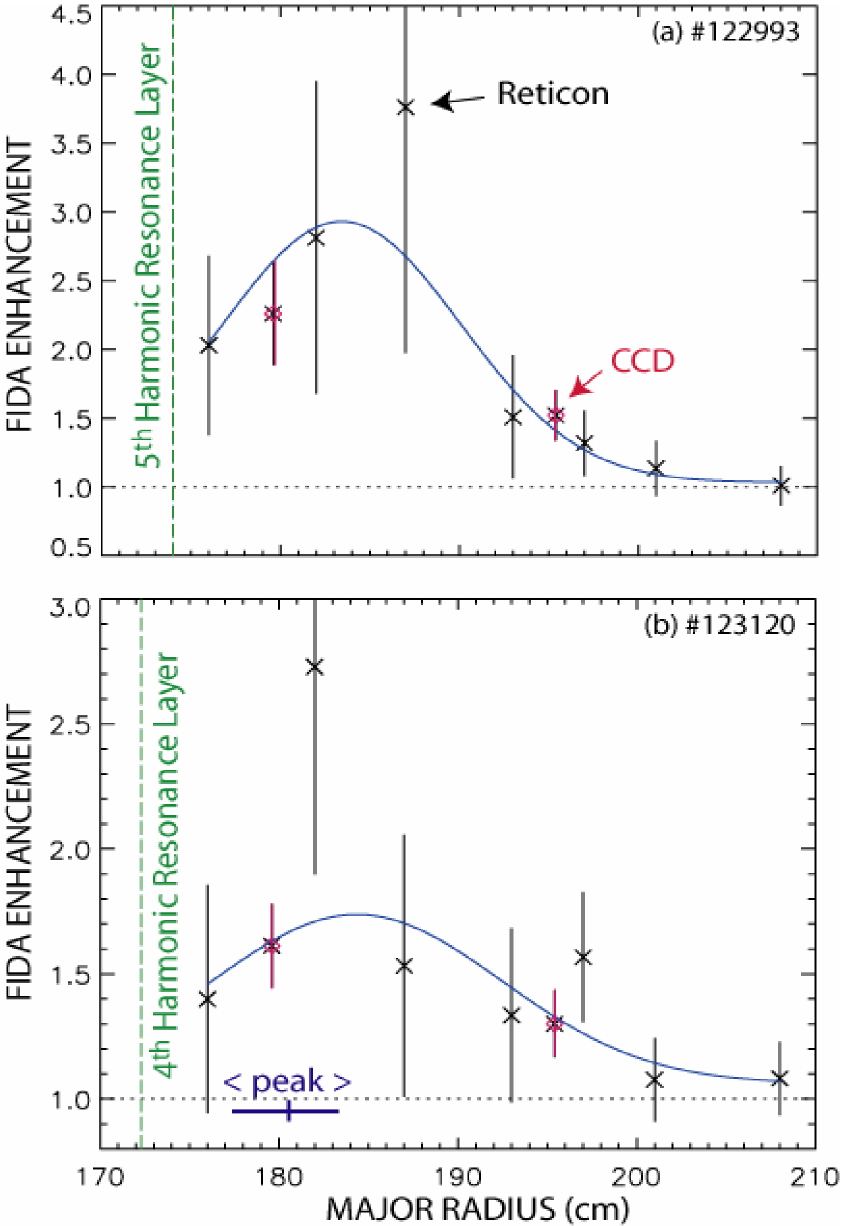
The Fast-ion Acceleration occurs in Core

- Fast-ion pressure exceeds classical (no RF) prediction for 5th & 4th harmonic case but not high-density case
- FIDA profiles show similar trends.
- The FIDA data are averaged over wavelength and time, then normalized to the no-RF profile.



The Peak of the FIDA Profile is at Larger Major Radius than the Resonance Layer

- For the 5th harmonic case, the profile peaks ~10 cm farther out than the resonance layer.
- For similar 4th harmonic cases, the profile peak is ~ 8 cm beyond the resonance layer.
- Errors are smaller for dedicated (CCD) diagnostic than for Reticon channels.



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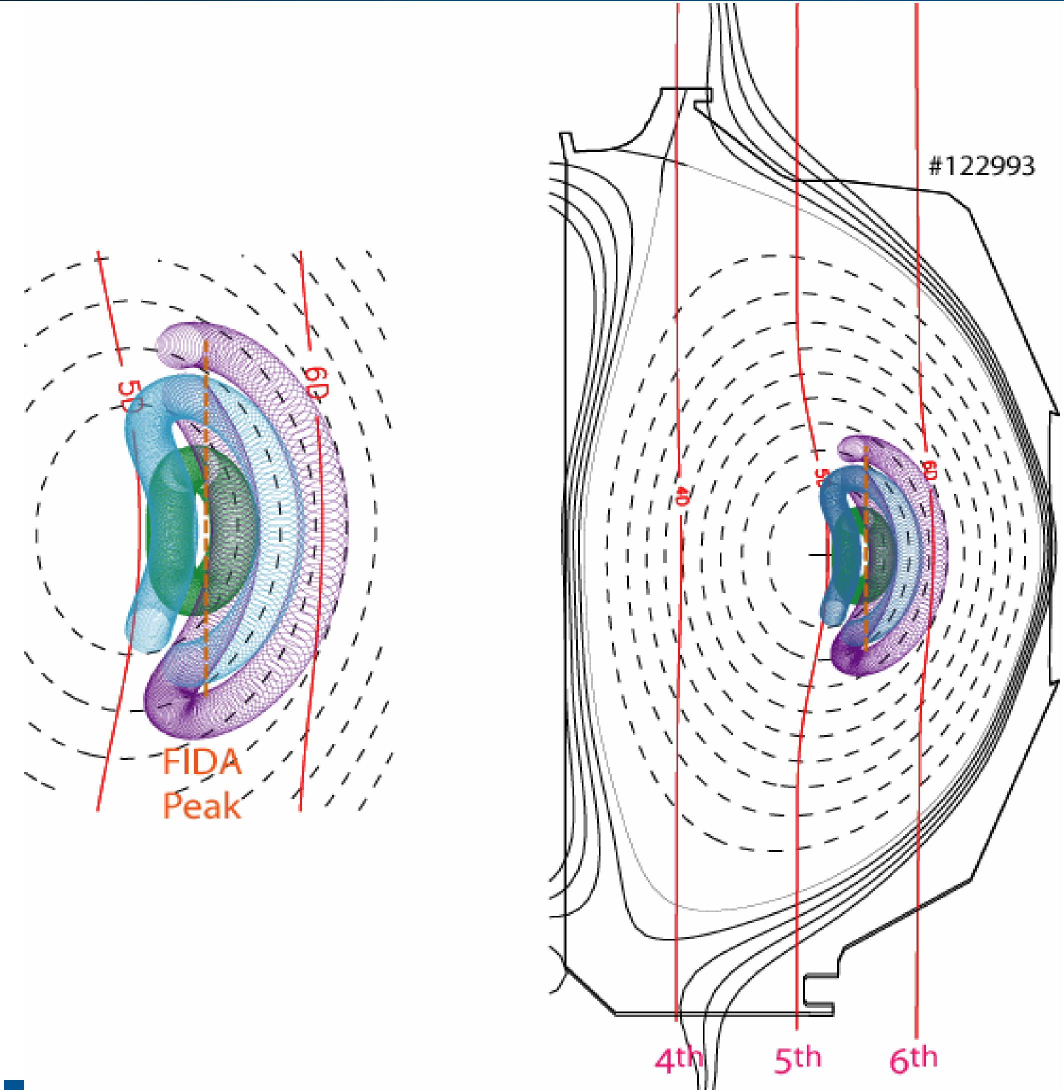
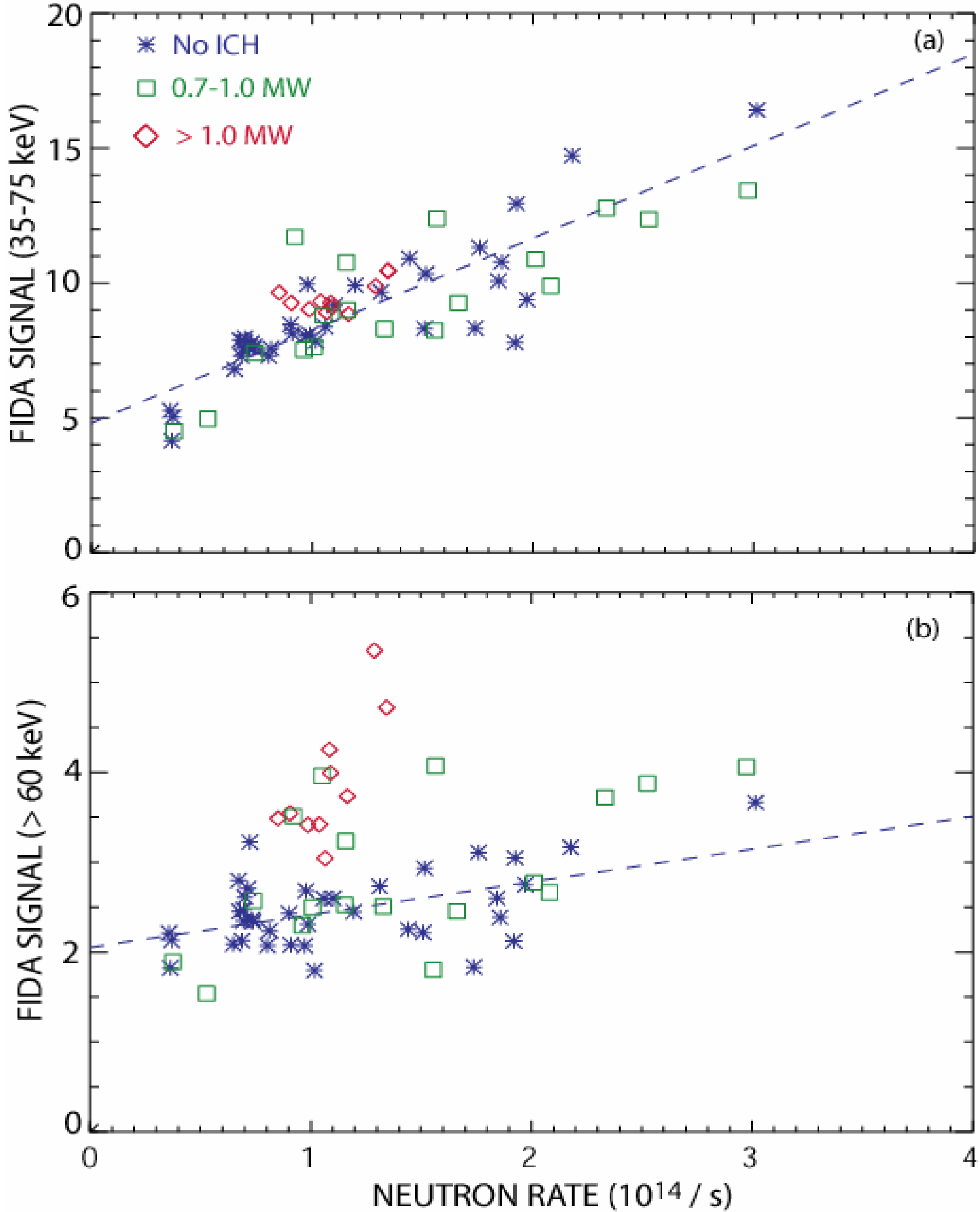
Likely Explanation for Outshifted FIDA Signal: Orbit Effects



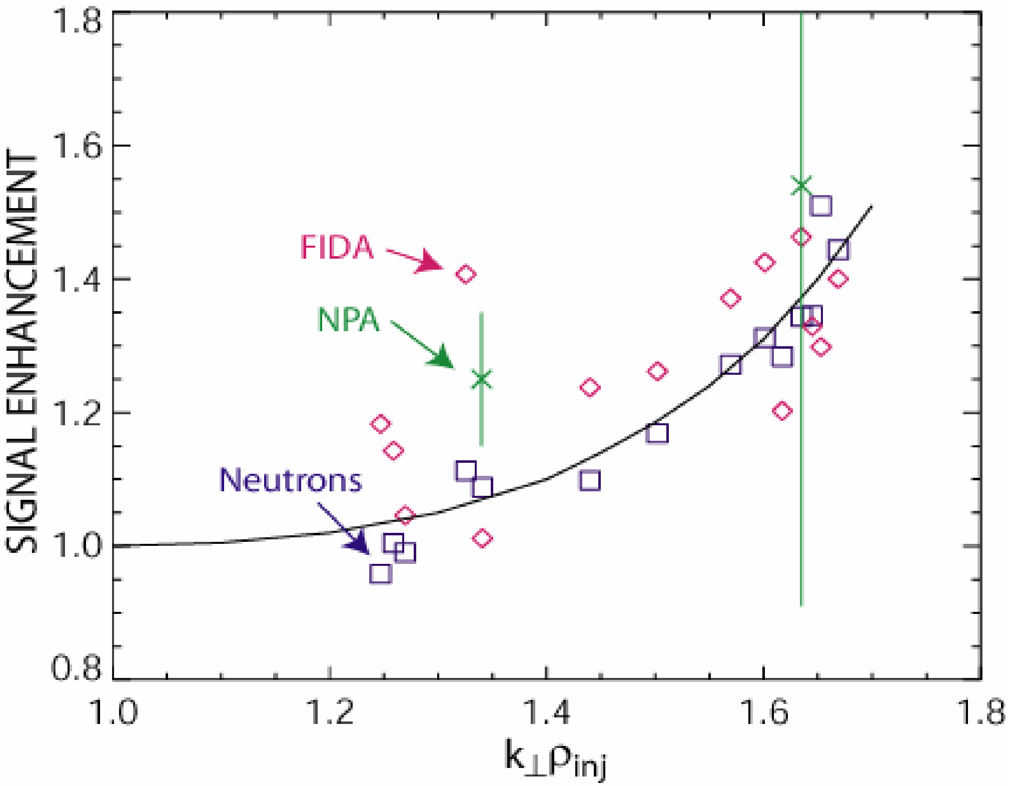
- Launch orbits in FIDA spatial volume with values of v_z that contribute strongly to the FIDA enhancement
- Representative orbits have turning points near the resonance layer.

The FIDA and Neutron data are consistent

- The "bulk" FIDA signal correlates well with the neutron rate
- Weak ICH power dependence for bulk-neutron comparison.
- In contrast, the "tail" FIDA signal has a strong additional dependence on ICH power



General trends are clearest for diagnostics that average the distribution function



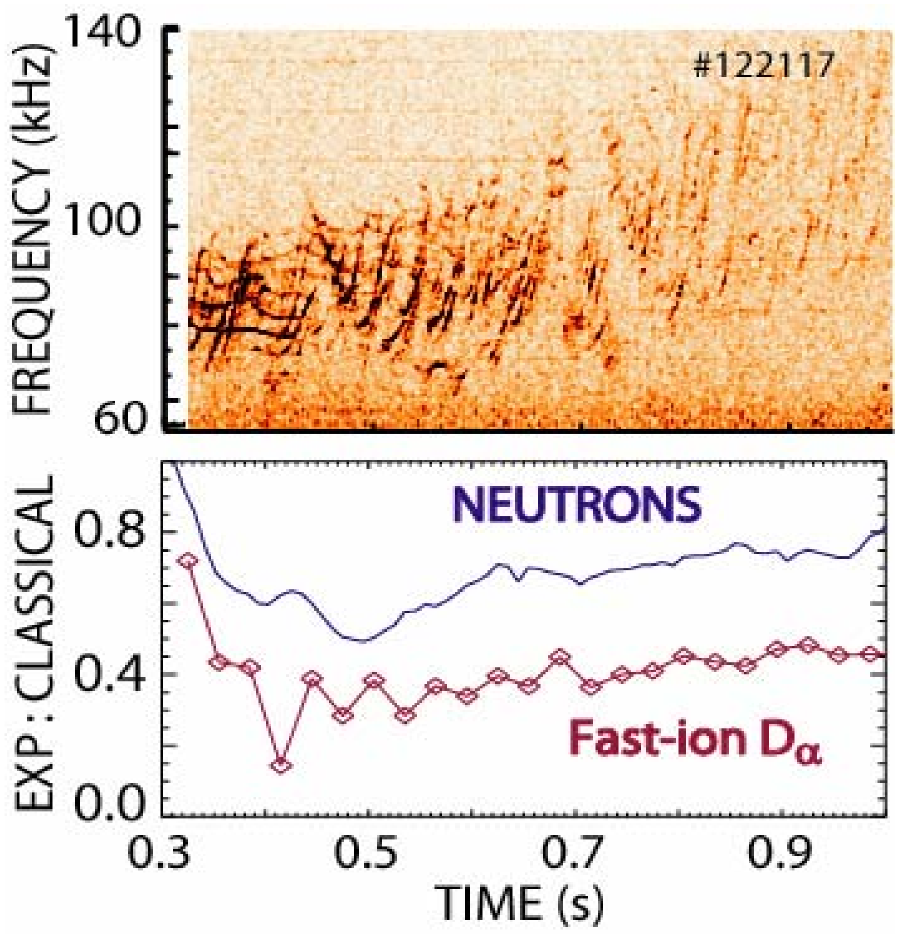
- The neutron enhancement for the 2005 data is consistent with the 1998 data and the predictions of a simple 0D model.*
- The FIDA data show more scatter, presumably due to greater sensitivity to spatial and velocity variations.
- The scatter in the NPA enhancement is huge

*Heidbrink, NF 39 (1999) 1369.

ICH Conclusions

- FIDA data are useful for diagnosing the temporal, spatial, and energy dependence of ion cyclotron heating (but the errors are large in some cases).
- The data are corroborated by neutron, NPA, and kinetic EFIT data.
- The fast-ion distribution function is distorted at high energies during ICH heating.
- The FIDA spatial profile peaks at larger major radius than the nominal resonance layer.
- The different diagnostics are complementary: averaged diagnostics are best for general trends but local phase-space measurements are needed for detailed comparisons with theory.

Alfven Modes Degrade Fast-ion Confinement



- Volume-averaged neutron rate is below the classical TRANSP prediction during the strong Alfven activity
- Fast-ion D_α (FIDA) diagnostic measures the spectrum of fast ions with 5 cm spatial resolution*
- FIDA "density" near ρ_{qmin} is reduced during the strong Alfven activity
- Both deficits correlate with the strength of the Alfven activity

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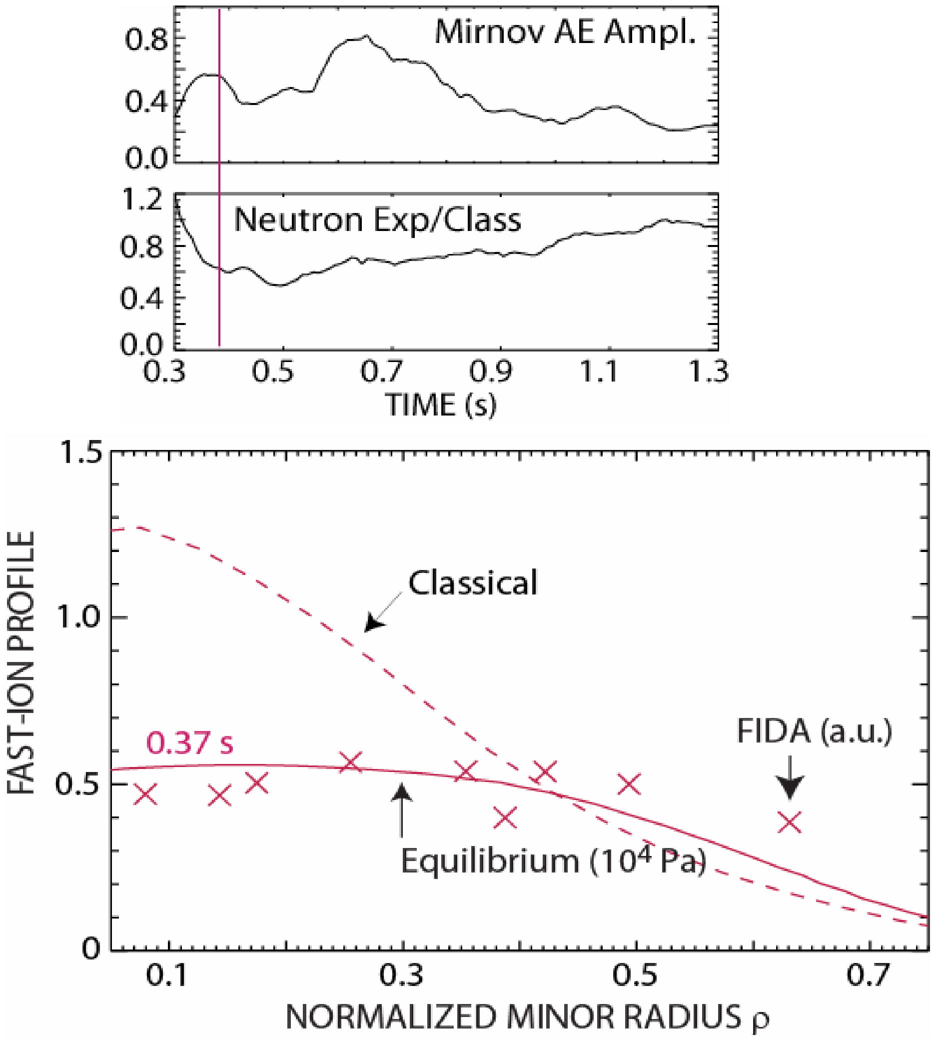
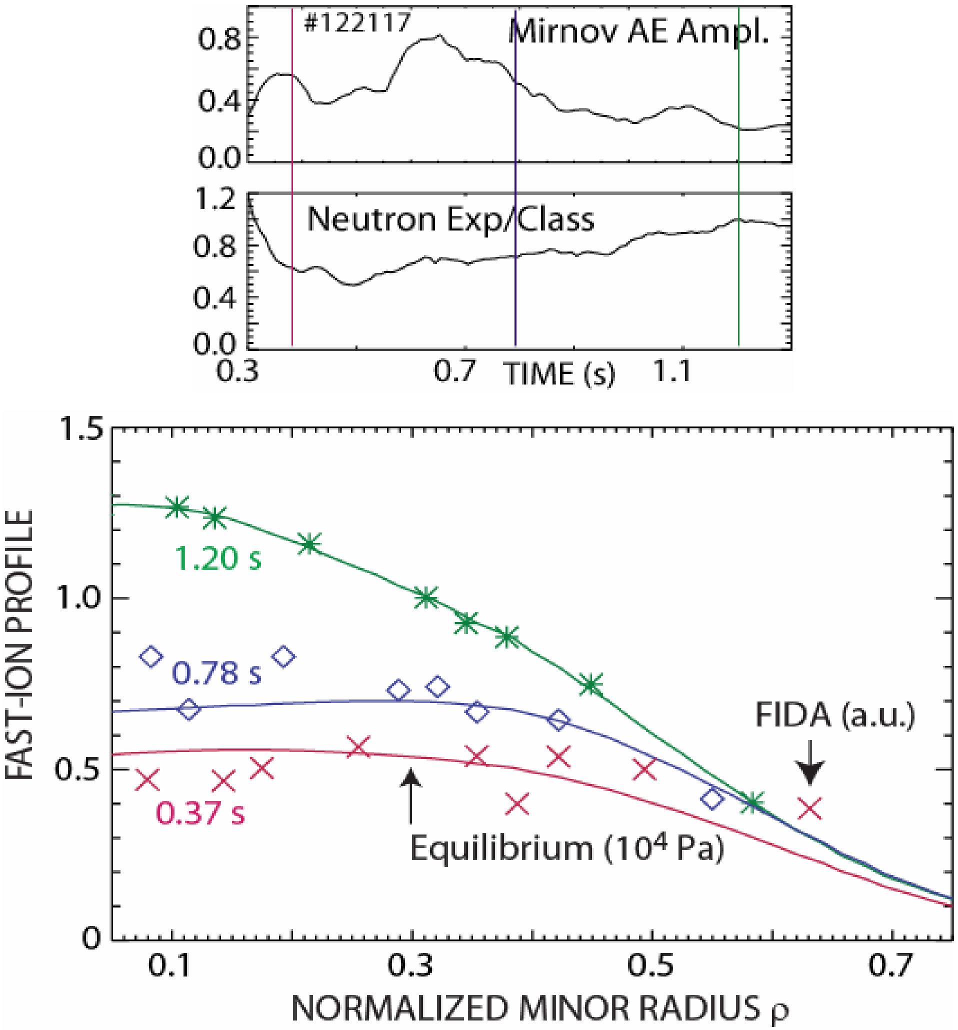
The Fast-ion Density Profile is Flattened



- During the strong Alfven activity, the fast-ion density profile from FIDA is nearly flat
- The fast-ion profile inferred from the equilibrium* is also very flat
- The classical profile computed by TRANSP peaks on axis

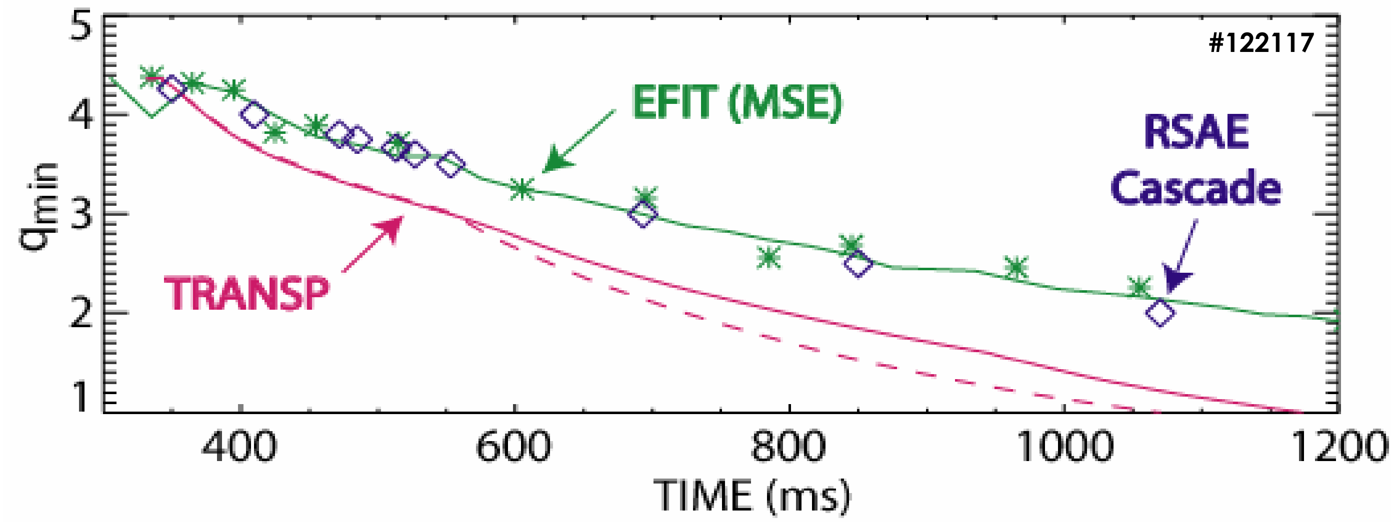
The Fast-ion Density Profile is Flattened



- The profile peaks up as the Alfven activity weakens
- The profile is still broader than classically predicted at 1.20 s.

The FIDA profile has been normalized to the equilibrium profile at 1.20 s. Only the relative change in shape is meaningful.

Fast-ion Transport Broadens the Profile of Neutral-Beam Driven Current



- The current diffuses more slowly than classically predicted
- Independent determinations of q_{min} from MSE-based equilibrium reconstructions and from the RSAE integer q crossings agree
- Apparently co-circulating fast ions that move to $\rho \sim 0.5$ broaden the NBCD profile.*

*Ferron, IAEA (2006); Wong, PRL 93 (2004) 085002; Wong, NF 45 (2005) 30.

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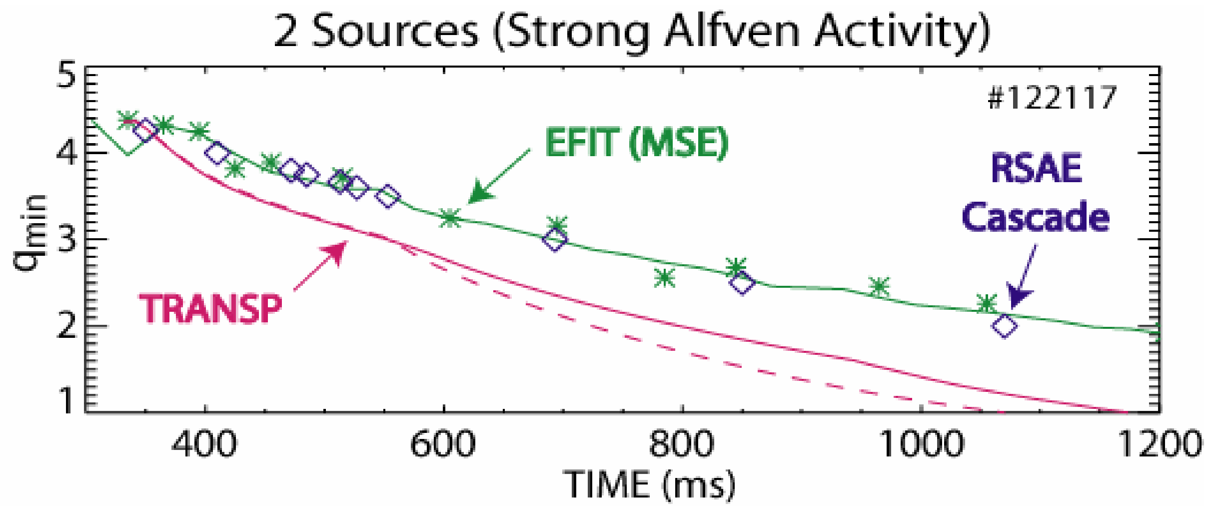
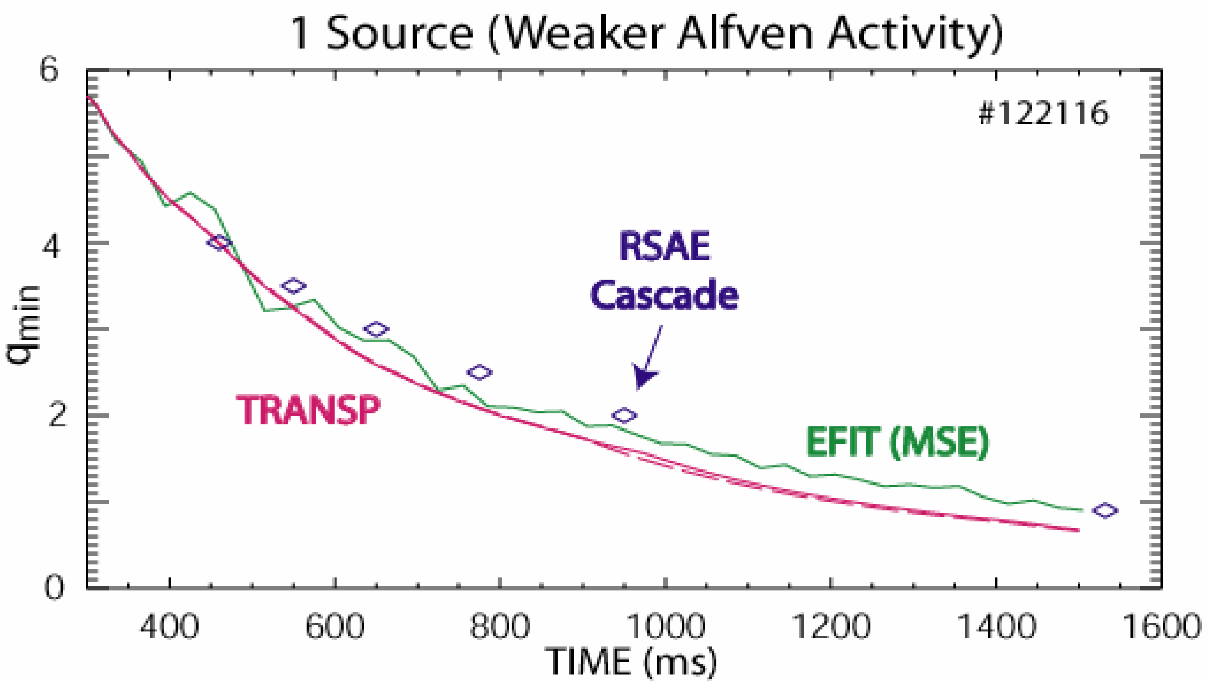
Solid TRANSP line is with normal NBCD; dashed line is with *no* NBCD.

The q-profile Evolution is close to classical in the one-source shot





Four Independent Measurements Provide Conclusive Evidence of Fast-Ion Transport

Volume-Averaged Neutrons

- Rate is below classical value
- Deficit correlates with Alfven amplitude
- Reduction corresponds to effective fast-ion diffusion of O(1 m^2/s).

Fast-ion D-alpha (FIDA)

- "Density" is suppressed during strong Alfven activity on central channels
- Profile peaks up as Alfven activity diminishes

Fast-ion Pressure Profile from Equilibrium (MSE)

- Profile peaks up as Alfven activity diminishes
- Profile broader than classical prediction

q_{min} Evolution (Alfven spectroscopy and MSE)

- Implies off-axis neutral-beam current drive (NBCD)

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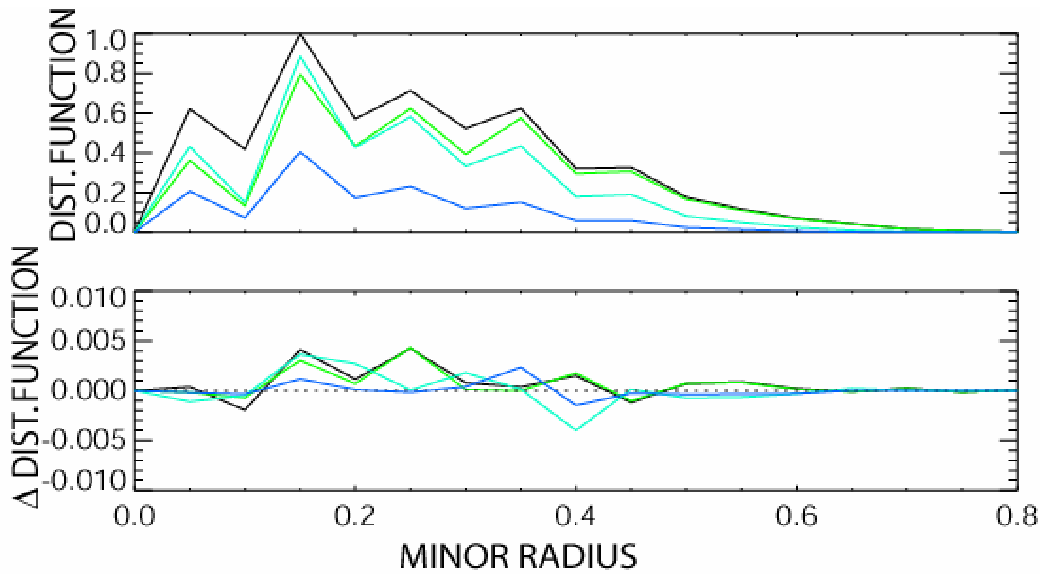
ORBIT Simulations Do *Not* Explain Flattened Profile



- Mode structure from NOVA/ECE comparison*
- 11 Toroidal TAEs and RSAEs at 5 times measured amplitude
- Simulation run for 0.3 ms

Transport mechanism is *not* a convective fishbone-like beacon

*Van Zeeland, PRL 97 (2006) 135001

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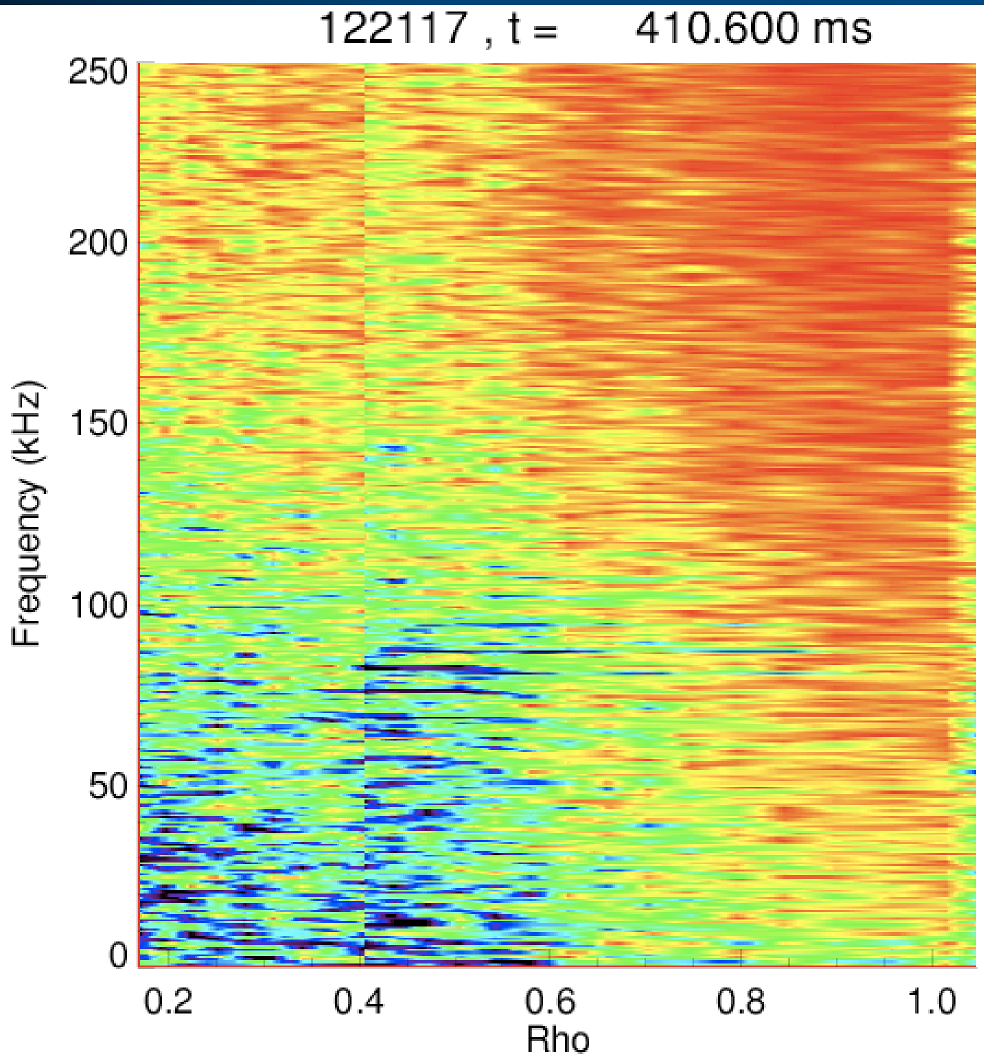
Does the "Sea" of Activity Cause Diffusive Transport?

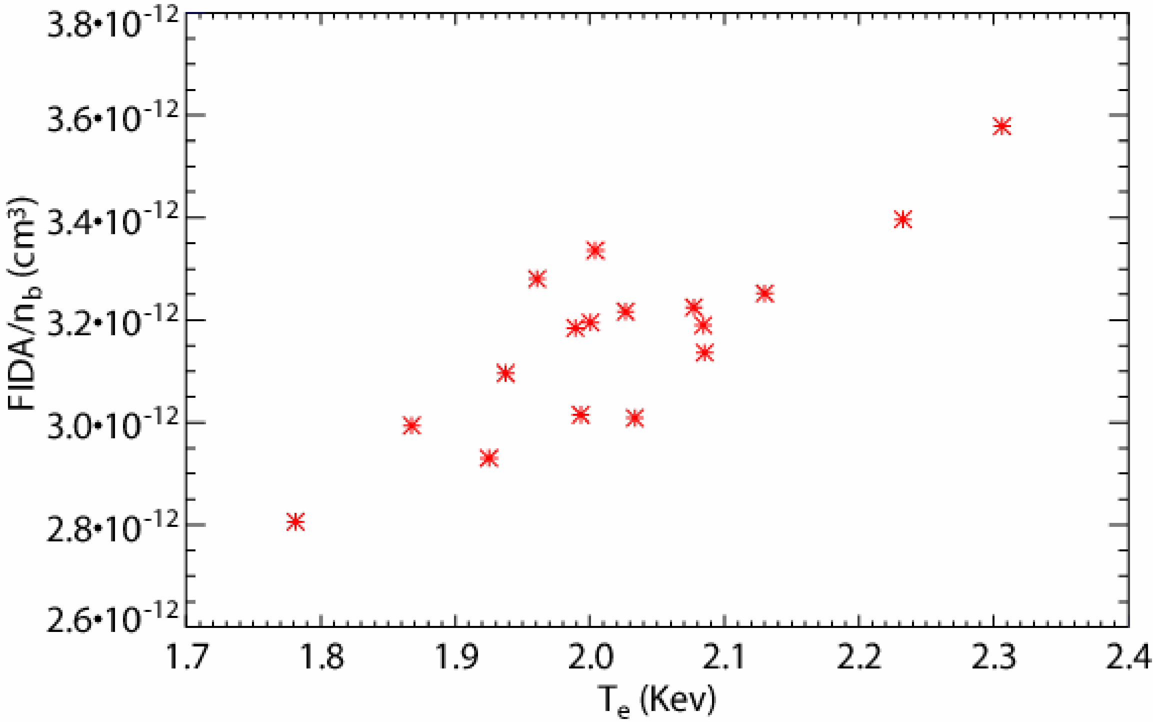


- ECE Data (Blue is strong)
- Many modes that constantly change

Conclusions

- **FIDA data make sense in quiet plasmas: spectra, intensity, radial profile**
- **Powerful diagnostic of fast-ion acceleration--comparison with CQL-3D and ORBIT-RF in progress.**
- **Clear flattening of fast-ion profile in plasmas with strong Alfven activity--still seeking a theoretical explanation**

Electron temperature dependence observed in the database



- Longer slowing down time and more pitch angle scattering result in stronger FIDA signals
- Loose constraints on other relevant parameters due to limited database entries cause scattered points

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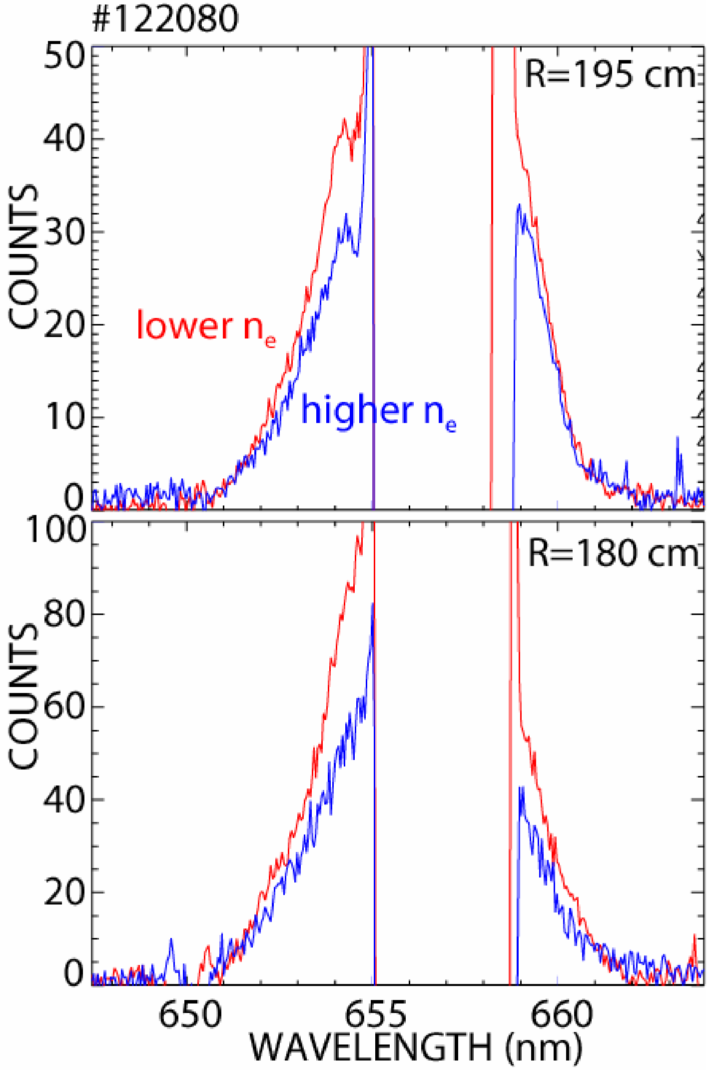
FIDA signal decreases when electron density increases



- FIDA signal decreases with n_e increasing because of shorter slowing down time (lower fast-ion density)
- For the chord at 180cm, electron temperature is nearly constant and signal decrease is solely caused by electron increase
- For the chord at 195cm, electron temperature with higher density is 15% higher offsetting portion of the FIDA signal drop

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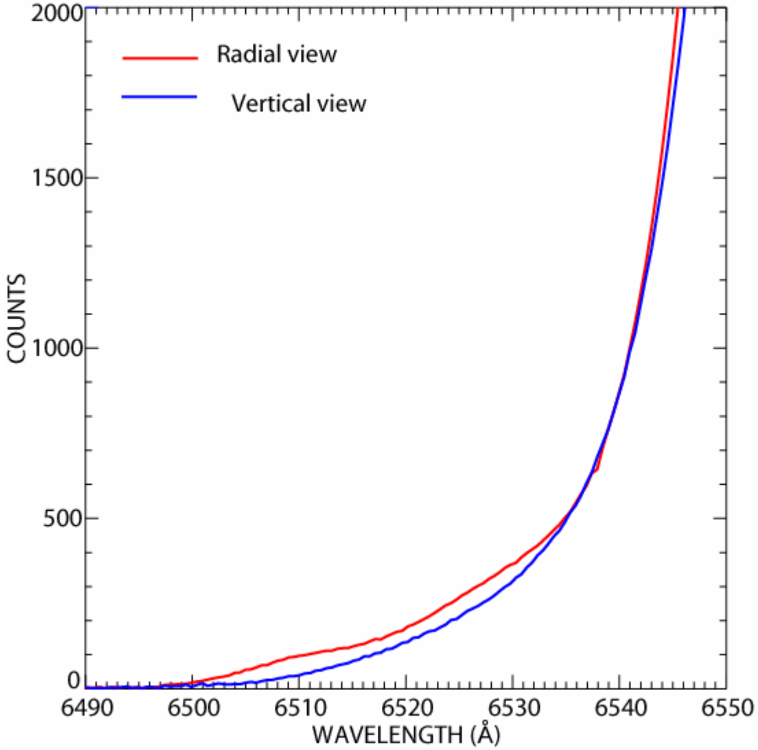
FIDA view dependence understood



- The red shifted side of the radial view is contaminated by beam emission
- Much stronger signal detected in the high energy range for the radial view
- Initial fast-ion pitch angle: 50.4^0. Pitch angle of radial view: 82.4^0. Pitch angle of vertical view: 91.1^0.

- **FIDA signal is stronger over the high energy range when pitch angle of viewing line is closer to the initial fast-ion pitch angle at chord location**

- **Implication:**

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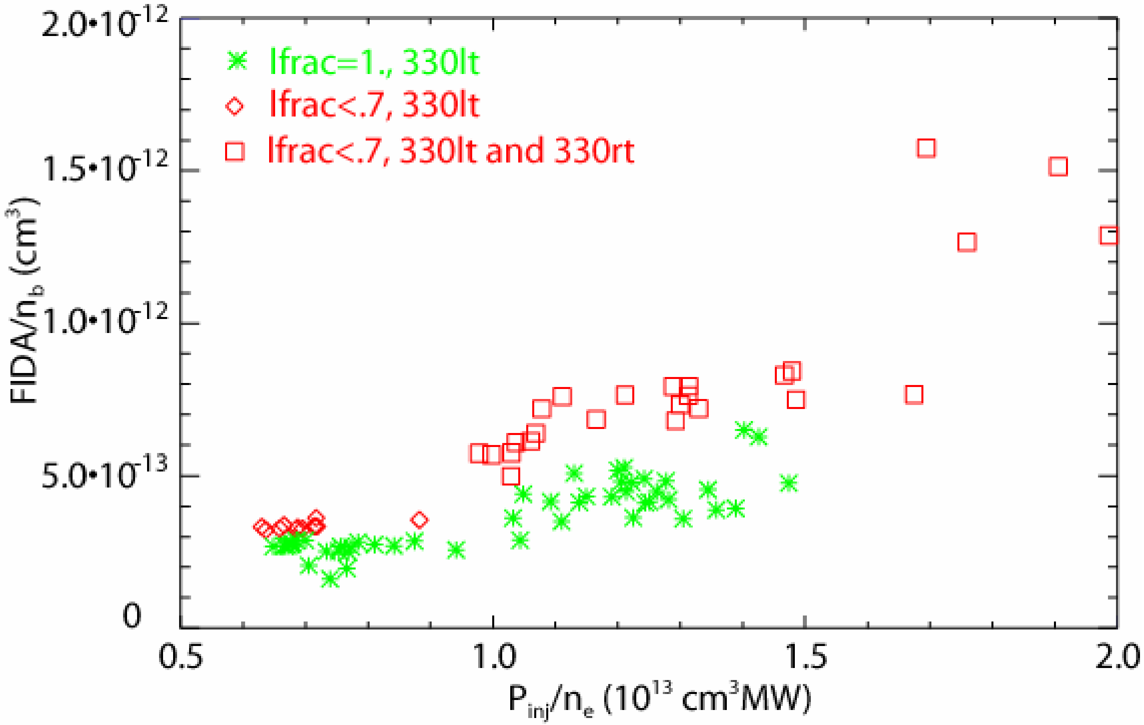
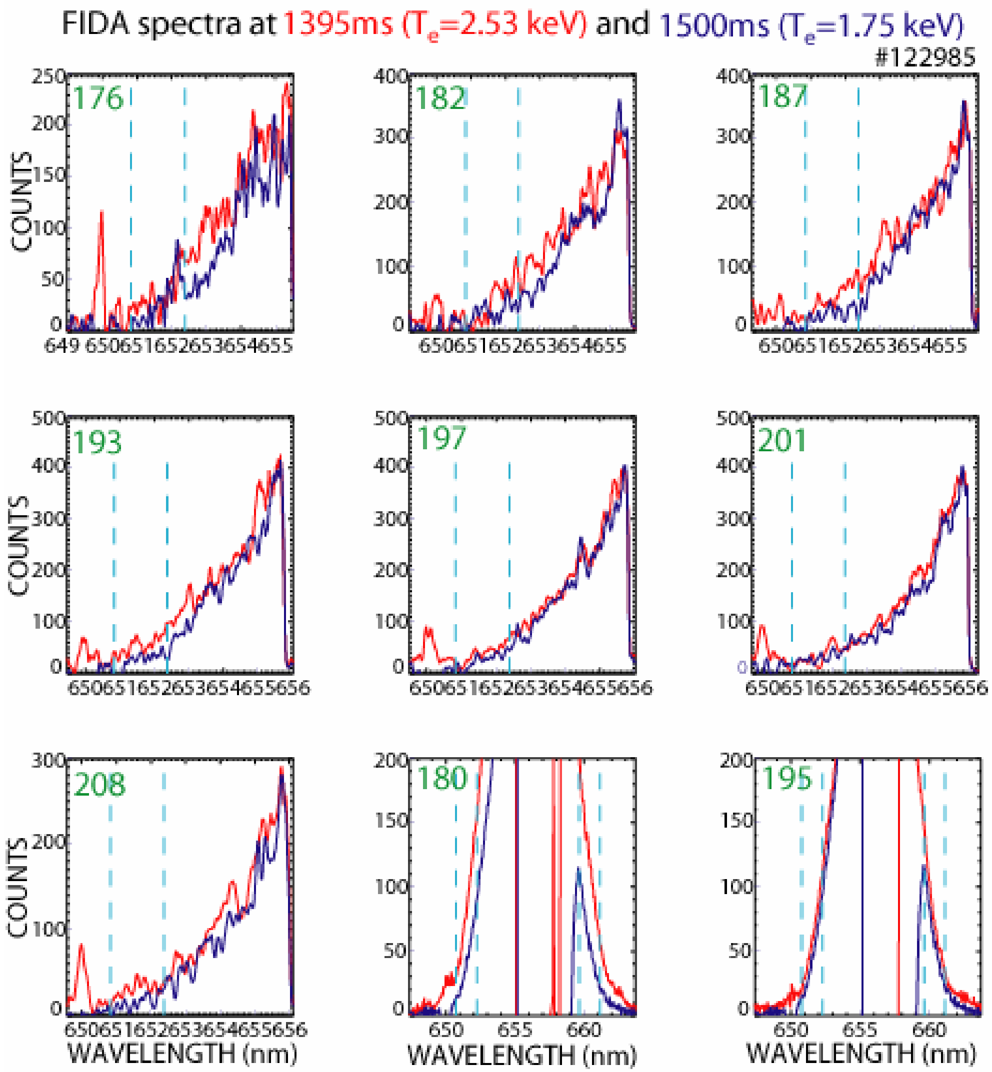
FIDA signal increases with beam power and decreases with left fraction



- $FIDA/n_b$ is proportional to fast-ion density
- P_{inj}/n_e is also proportional to fast-ion density if T_e held constant
- Electron temperature is held to be between 2 keV and 3 keV because of limited database entries

- Strong correlation observed between FIDA signal and beam power
- Signal increased with right beam source
- Chord views portion of 330 right beam

FIDA spectra with different electron temperatures



- FIDA provides radial profiles with two full spectra and seven partial spectra
- FIDA spectra is lower with lower electron temperature on all channels especially the central channels as expected

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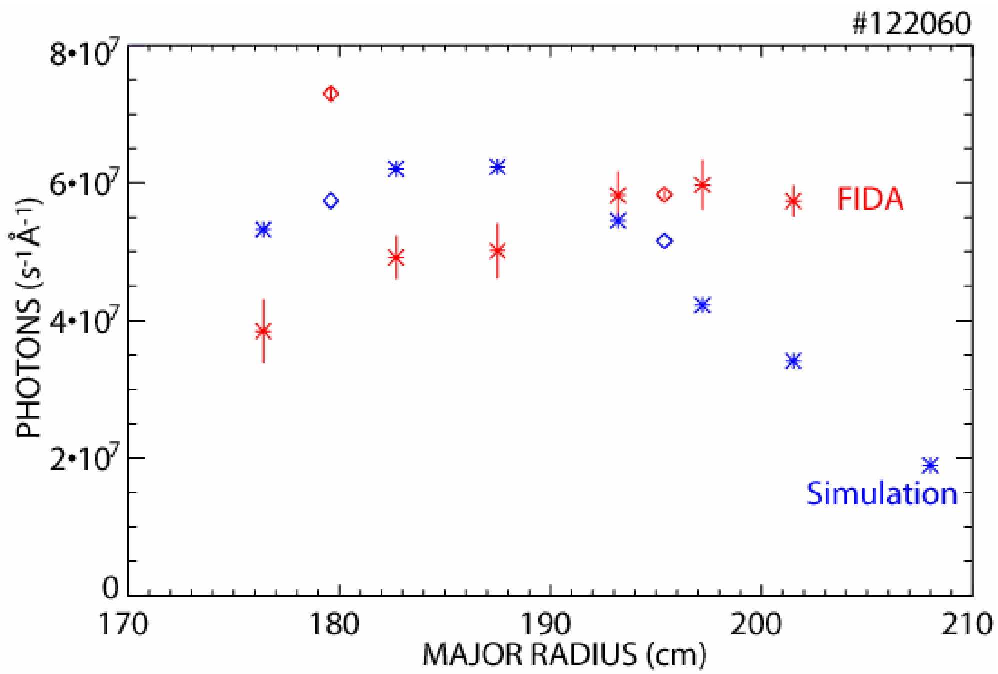
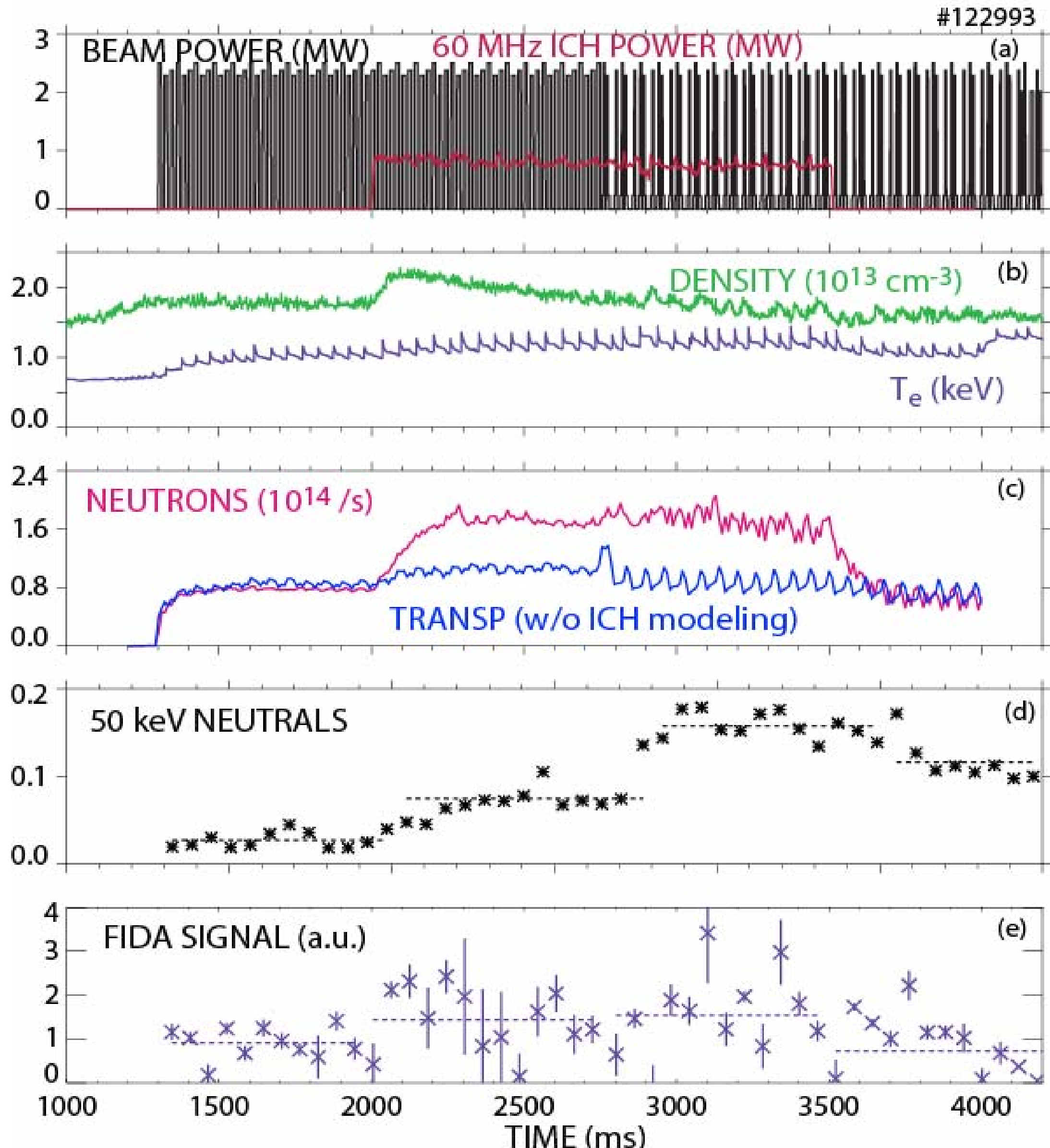
FIDA absolute radial profile is more challenging



- Simulated FIDA profile looks reasonable.
- The absolute magnitudes are within 30%. Not bad considering all the uncertainties.
- The profile shape doesn't agree with the simulation.
- The difference between CCD channels and Reticon channels suggests that the intensity calibration is problematic.
- Future prospect is good with careful intensity calibration.

Strong Acceleration in Low Power 5th Harmonic Case

- 1/2 Source → More power/particle
- Low density → Weak drag
- Large neutron enhancement
- Perpendicular NPA signal doubles
- FIDA temporal resolution relatively poor (fewer fast ions)
- FIDA signal ~ doubles



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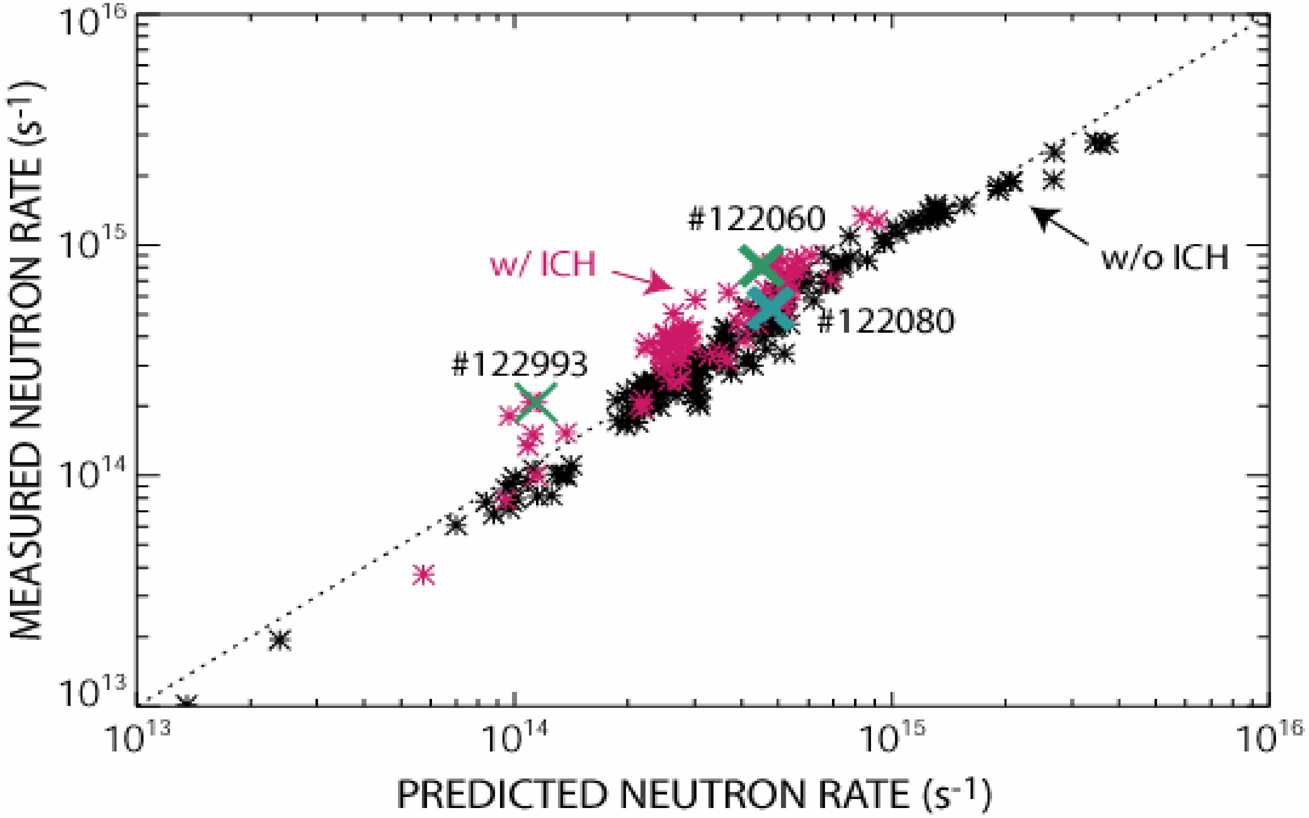
The Neutron Rate is often Larger than Classically Predicted during ICH



- Database of 2005 cases with steady plasma conditions and quiet MHD
- Predicted rate from 0D model

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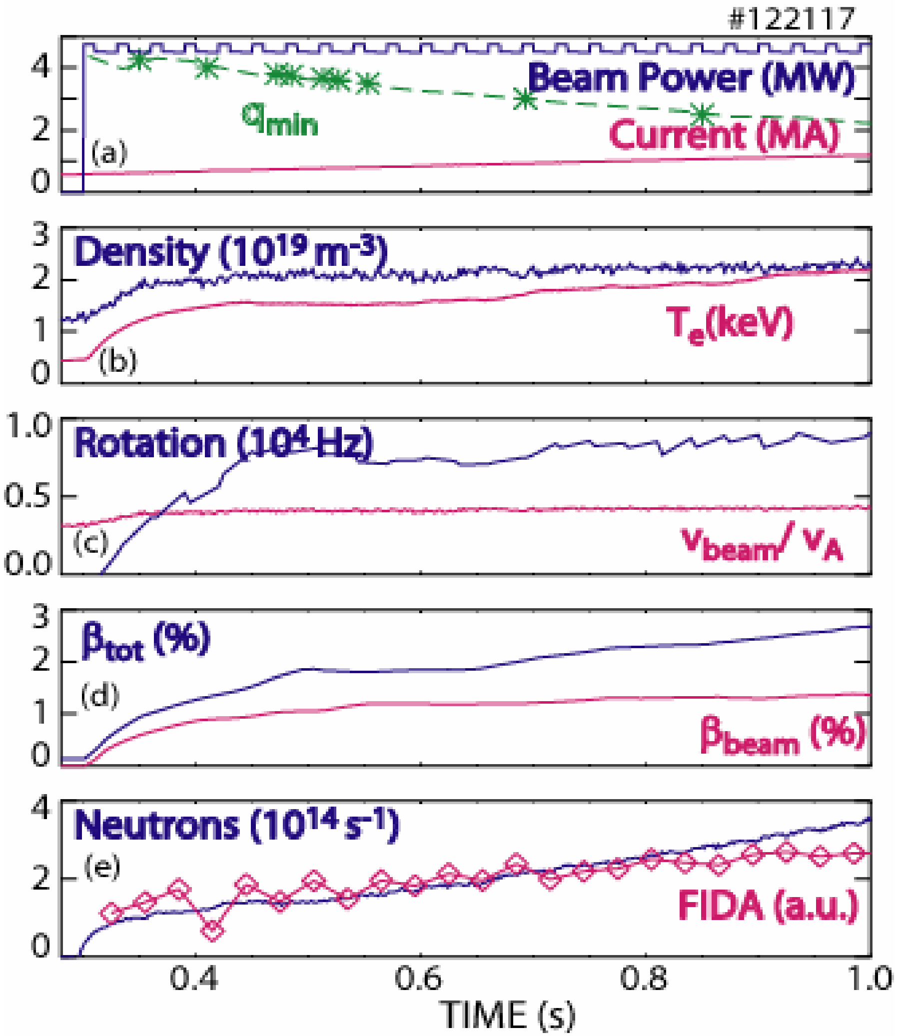
Alfven Modes are Usually Unstable in Advanced Tokamak (AT) Plasmas

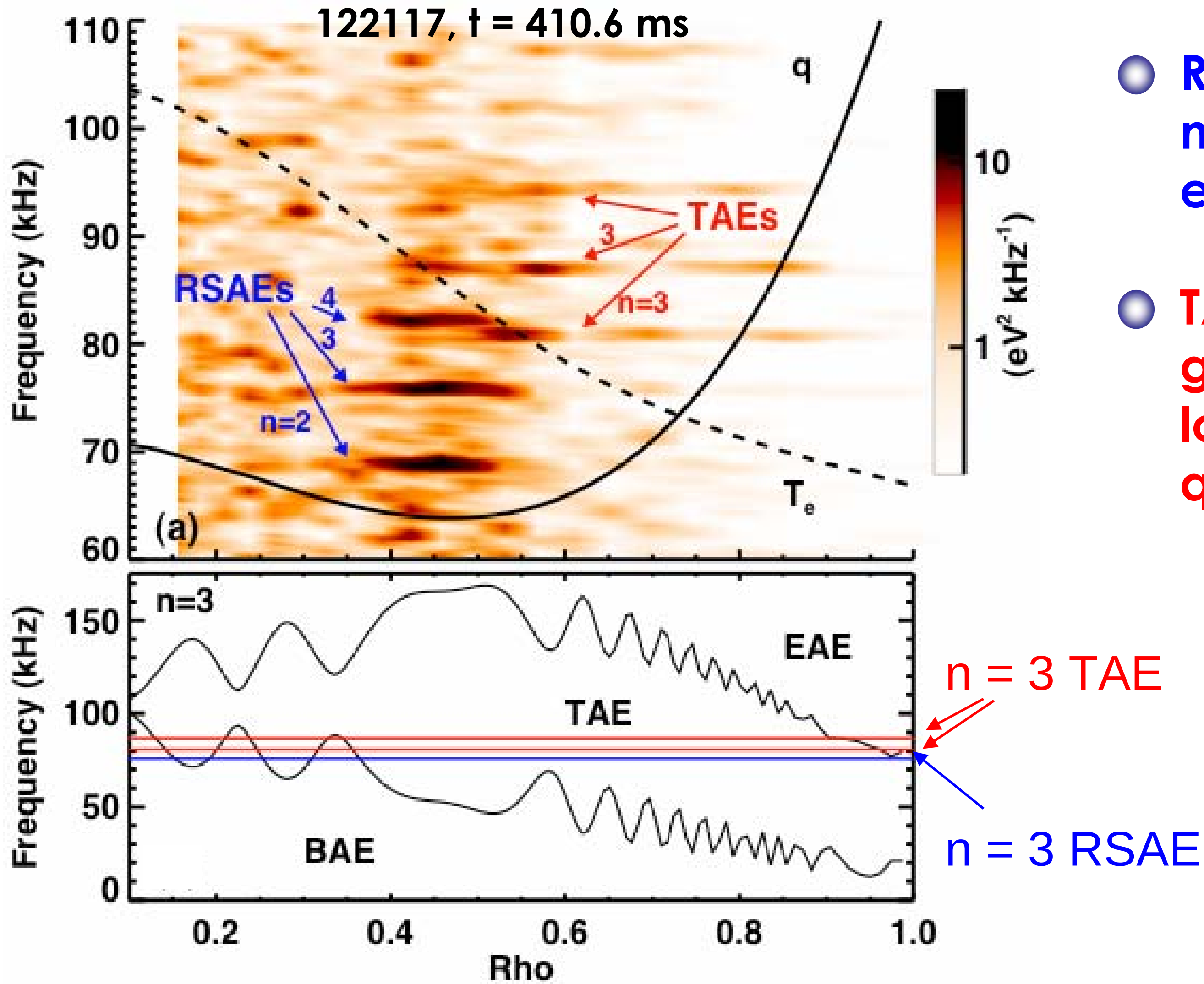


In this poster…

- Reversed shear with early beam injection
- 80 keV Deuterium Co-injection
- Modest density → large beam beta to drive modes
- Fast-ion speed > $v_A/3$ → circulating fast ions resonate with TAEs

- Qualitatively similar conditions in many plasmas → Alfven modes are common in DIII-D

Analysis of many ECE channels reveals AE structure



- **RSAE are peaked near q-min as expected**
- **TAE are more global and located outside of q-min**

n=3 Alfvén continuum consistent with modes being RSAEs and TAEs

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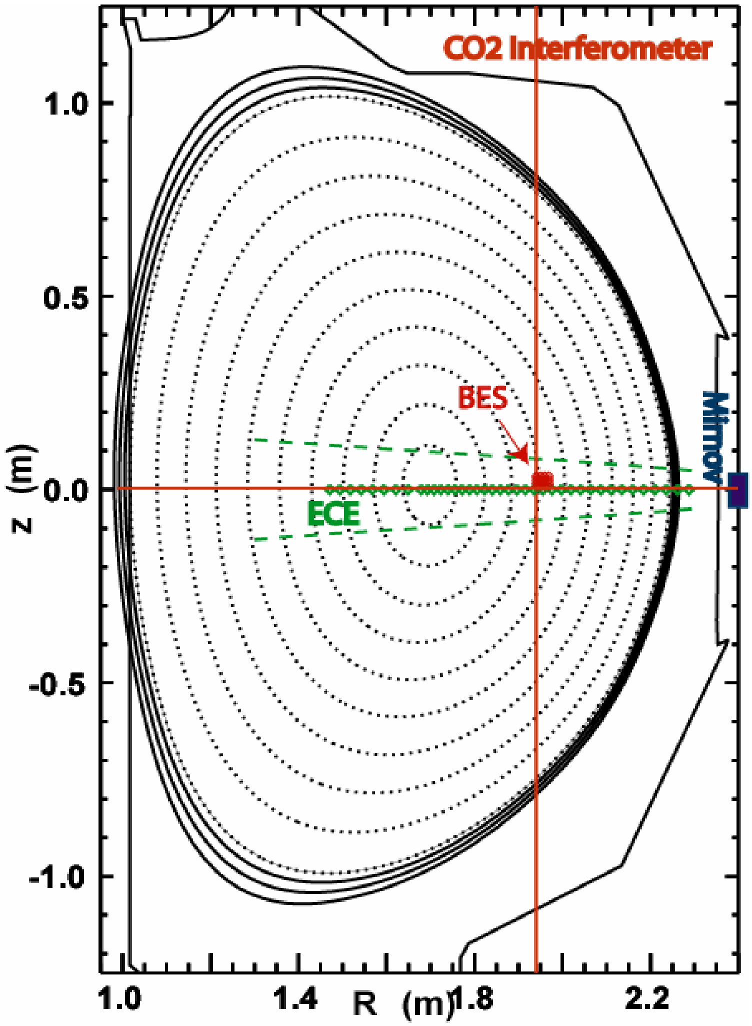
Signals Depend on the Mode Structure



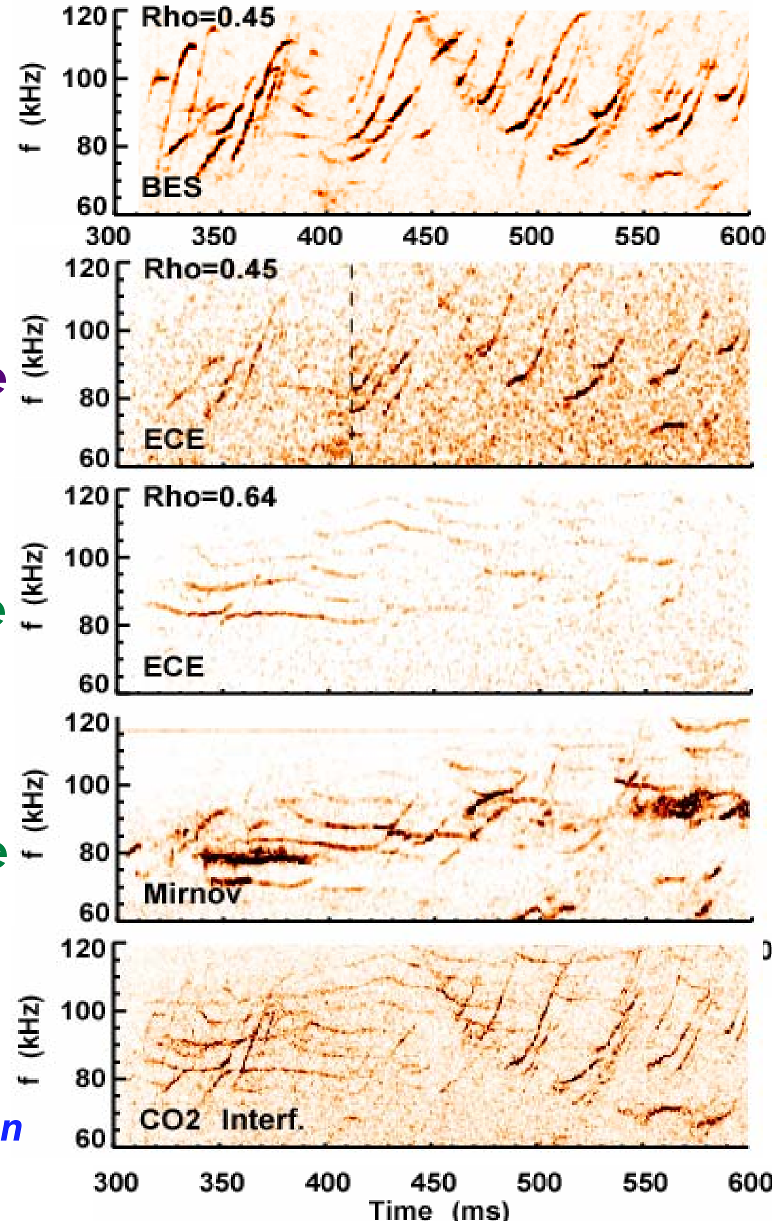
RSAEs dominate

RSAEs dominate

TAEs dominate

TAEs dominate

TAEs & RSAEs



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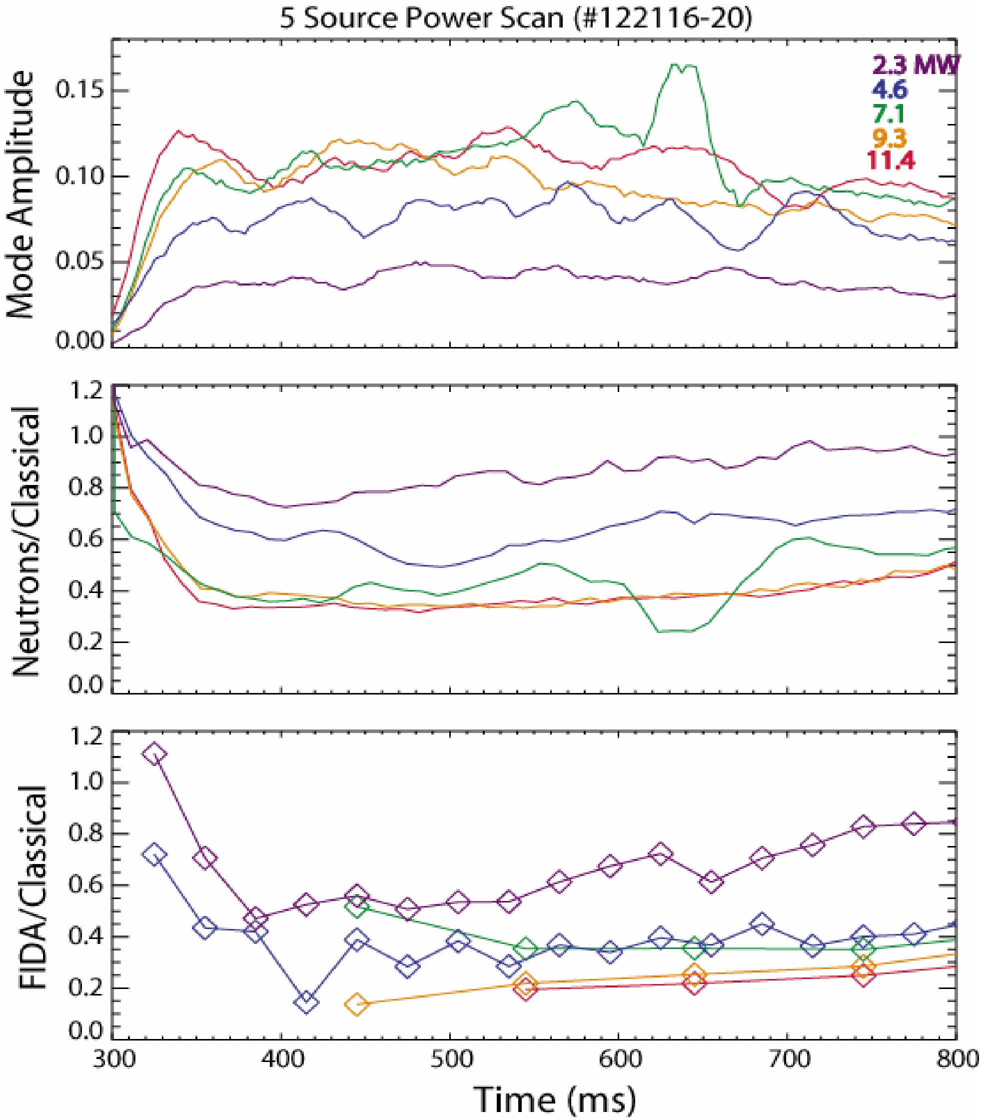
Van Zeeland, PPCF 47 (2005) L31; Nucl. Fusion 46 (2006) S880.

The Fast-ion Deficit Correlates with Alfven Activity

- The strength of the Alfven activity tends to increase with beam power in similar plasmas.
- The discrepancy between the classical prediction and the data is largest when the Alfven modes are strong
- The FIDA deficit is larger than the neutron deficit



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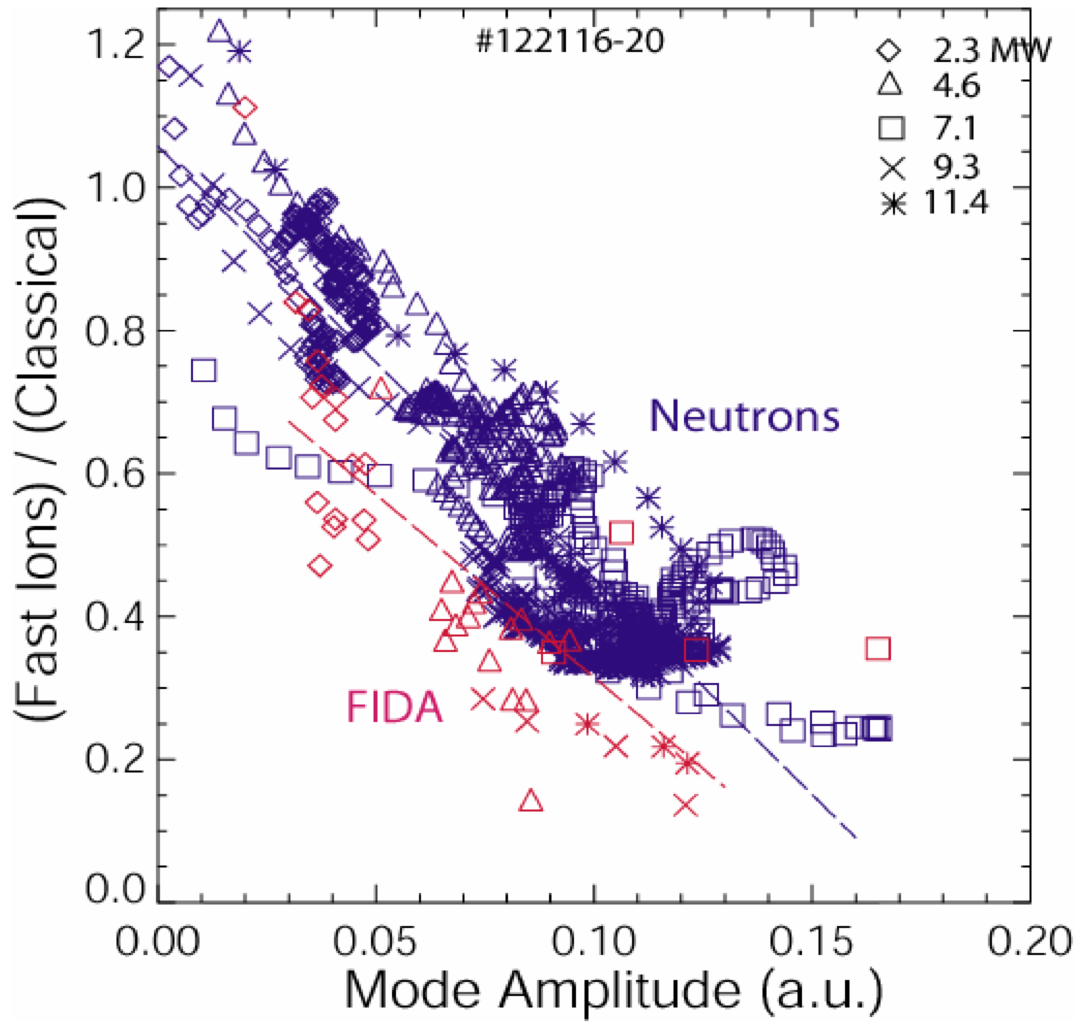
****For this comparison, the FIDA density and neutron rate are normalized by their values at 2.0 s in the 1-source shot (when Alfven activity is undetectable).***

The Fast-ion Deficit is Roughly Linear with Mode Amplitude

- Same power-scan data as previous page
- The FIDA deficit for channel near ρ_{qmin} is larger than the neutron deficit



**For this comparison, the FIDA density and neutron rate are normalized by their values at 2.0 s in the 1-source shot (when Alfven activity is undetectable).*