Three types of Tokamak Fast-ion Transport of Relevance to Stellarators

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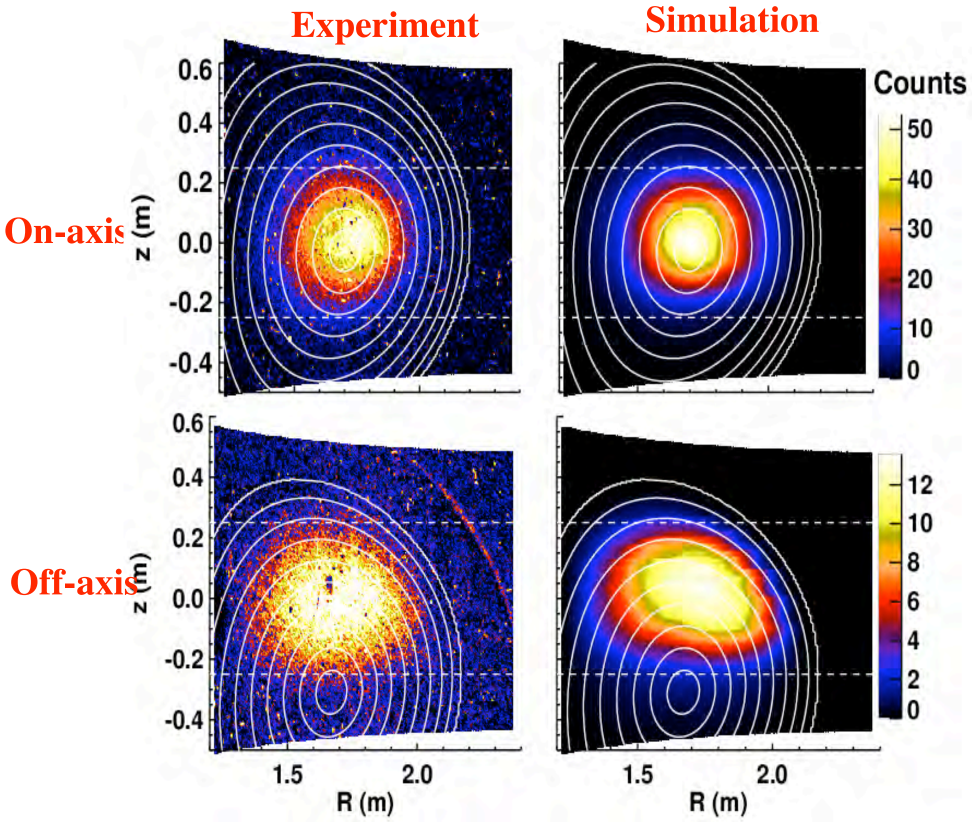
Fast-ion D_α (FIDA) Images



Outline (3 mechanisms of fast-ion transport)

1) Orbit stochasticity

Fast-ion D-alpha (FIDA) diagnostic

2) Drift-wave turbulence

3) Many small-amplitude Alfvén modes

Outline

1) Orbit stochasticity

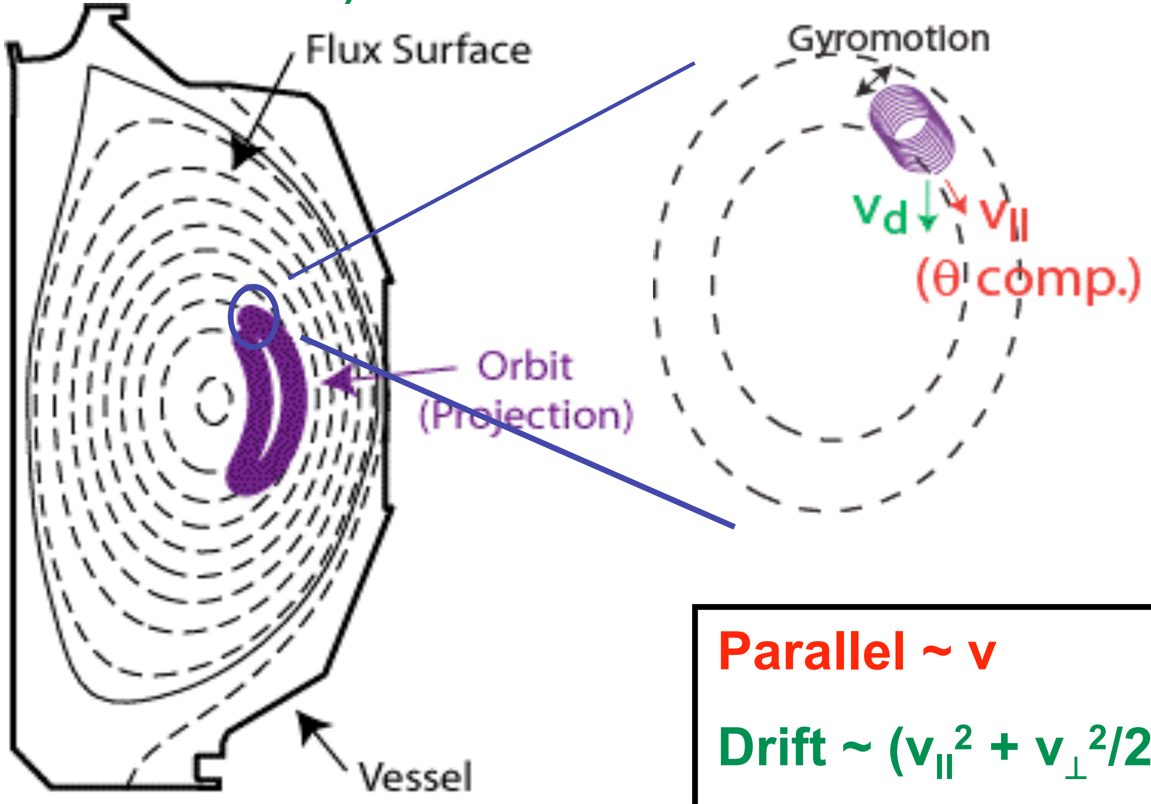
Fast-ion D-alpha (FIDA) diagnostic

2) Drift-wave turbulence

3) Many small-amplitude Alfvén modes

Fast-ion orbits have large excursions from magnetic field lines

Elevation (80 keV D$^+$ ion in DIII-D)



- Perp. velocity ◊ gyromotion
- Parallel velocity ◊ follows flux surface
- Curvature & Grad B drifts ◊ excursion from flux surface

Parallel ~ v

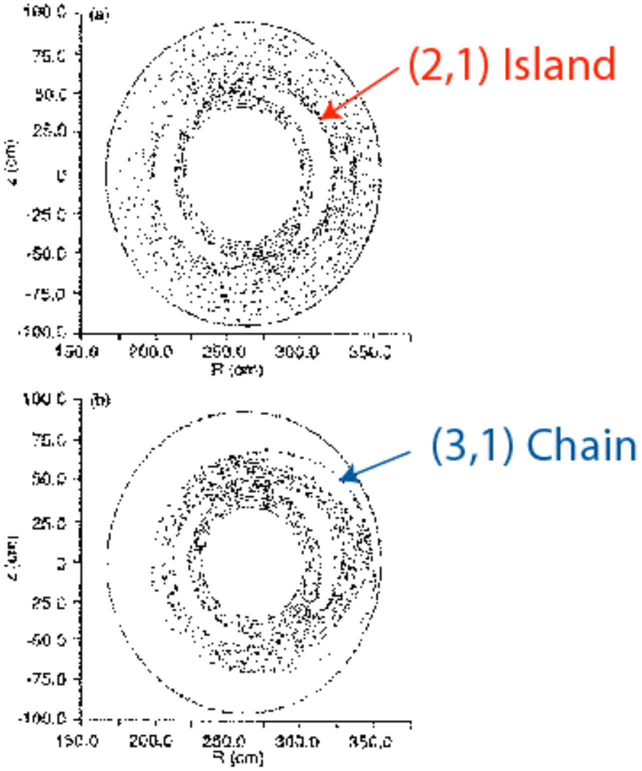
Drift ~ $(v_{||}^2 + v_\perp^2/2)$

◊ Large excursions for large velocities

$\delta\rho_3) > (\rho_3 - \rho_2) = 0.17$

Stochasticity caused by beating of drift orbit with helical field

- **Curvature drift: orbit has an m=1, n=0 perturbation**
- **MHD mode: m=2, n=1 perturbation**
- **Beating produces m=3, n=1 island chain**
- **(2,1) MHD island width:** $\delta\rho_2 = 0.26$
- **(3,1) orbit island width:** $\delta\rho_3 = (0.25)\delta\rho_2$

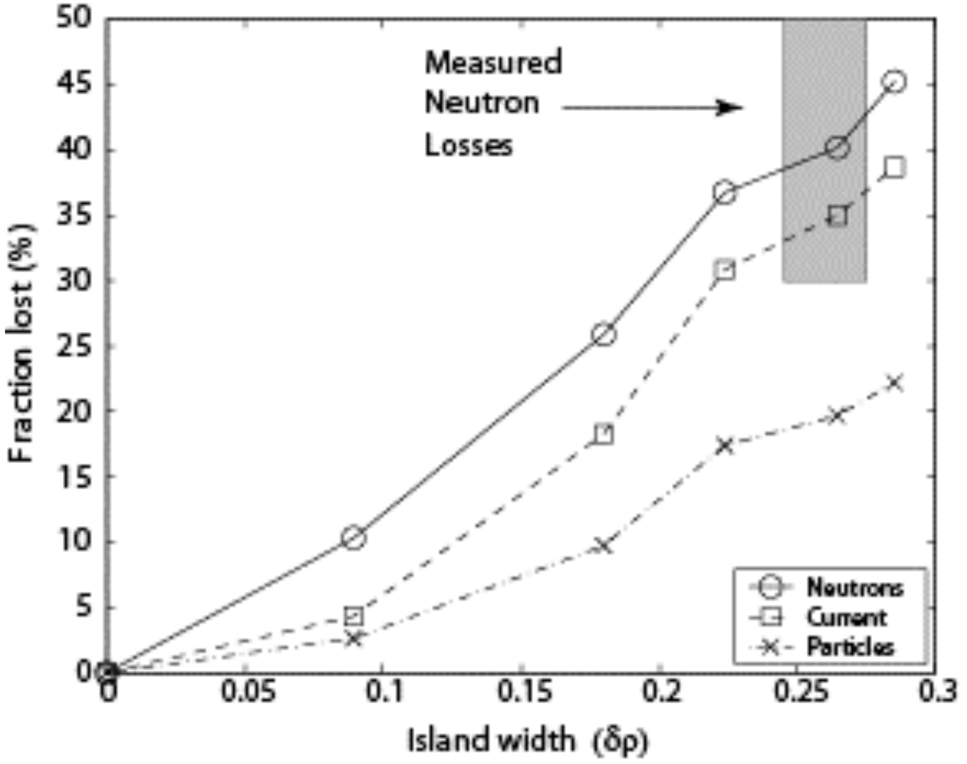


Mynick, Phys. Fl. B 5 (1993) 1471.

$$\delta\rho_2 + \delta\rho_3 \sim 2(\rho_3 - \rho_2) = 0.34$$

◊ **Stochastic**

Orbit stochasticity is observed experimentally



Carolipio, Nucl. Fusion 42 (2002) 853

- Fast ions from tangential neutral beam injection
- Enter tearing mode & fast ions in an orbit-following code
- Compute losses vs. island width ◊ calculations agree with experiment

Similar work: Zweben, Nucl. Fusion 39 (1999) 1097; García-Muñoz, Nucl. Fusion 47 (2007) L10; Pritchard, Phys. Pl. 4 (1997) 162.

Outline

1) Orbit stochasticity

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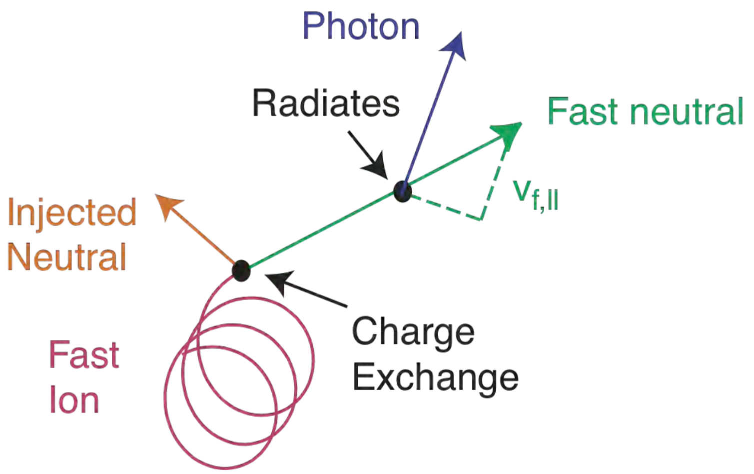
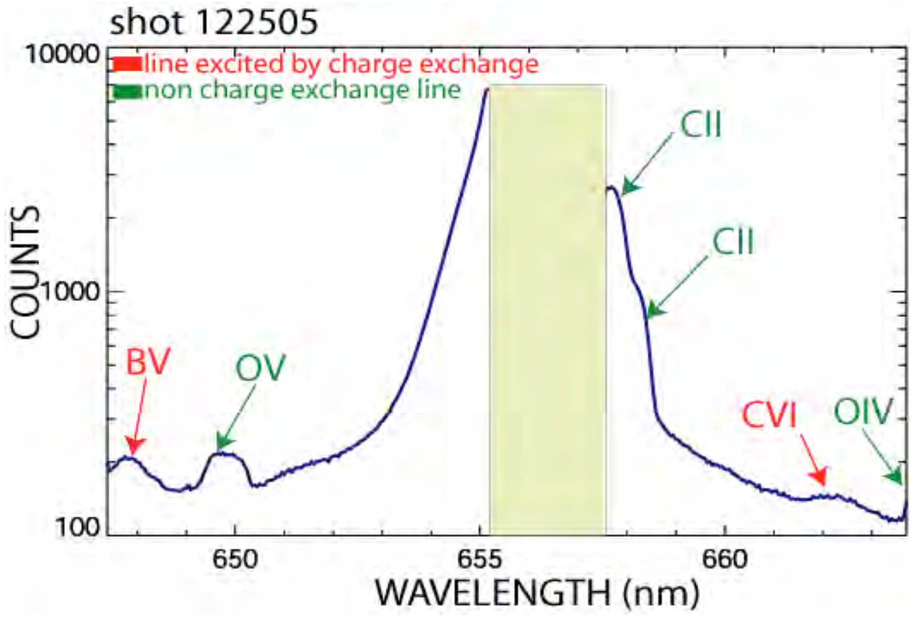
2) Drift-wave turbulence

3) Many small-amplitude Alfvén modes

FIDA measures Doppler-shifted light from fast ions



Heidbrink, PPCF 46 (2004) 1855

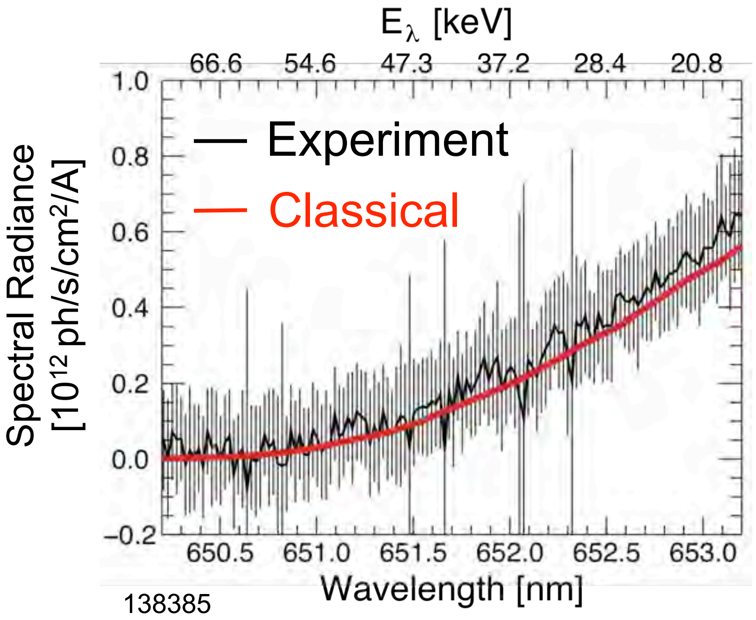


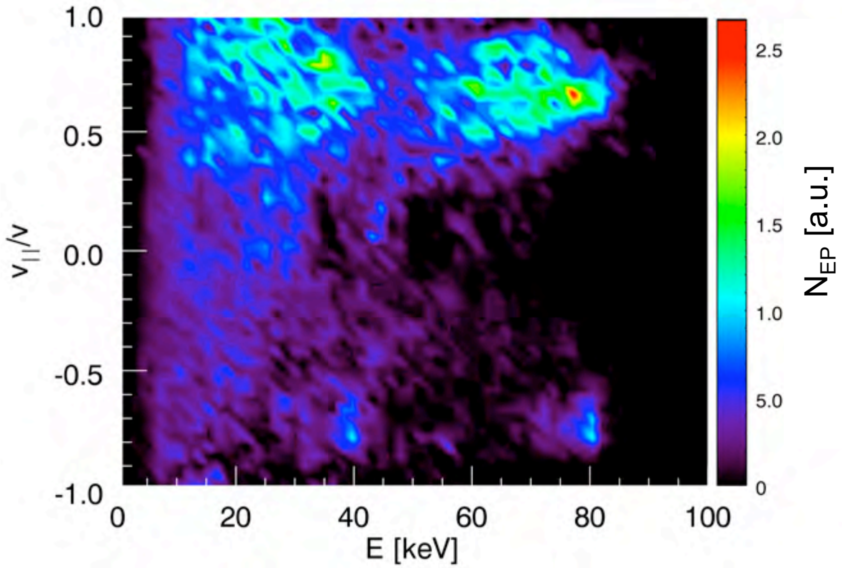
Luo, RSI 78 (2007) 033505

- A type of charge exchange recombination spectroscopy
- Use views that avoid bright interferences
- Exploit large Doppler shift (measure wings of line)
- Modulate beam for background subtraction
- Background subtraction dominates error

Use Forward Modeling to Compare Theory with Experiment

- **NUBEAM module of TRANSP***
  - outputs classical energetic ion distribution function
  - accepts user defined energetic ion diffusivity





- **FIDA Simulation****
  - generates expected FIDA spectra from input distribution function
  - **calculated spectra** compared to **calibrated FIDA channel**

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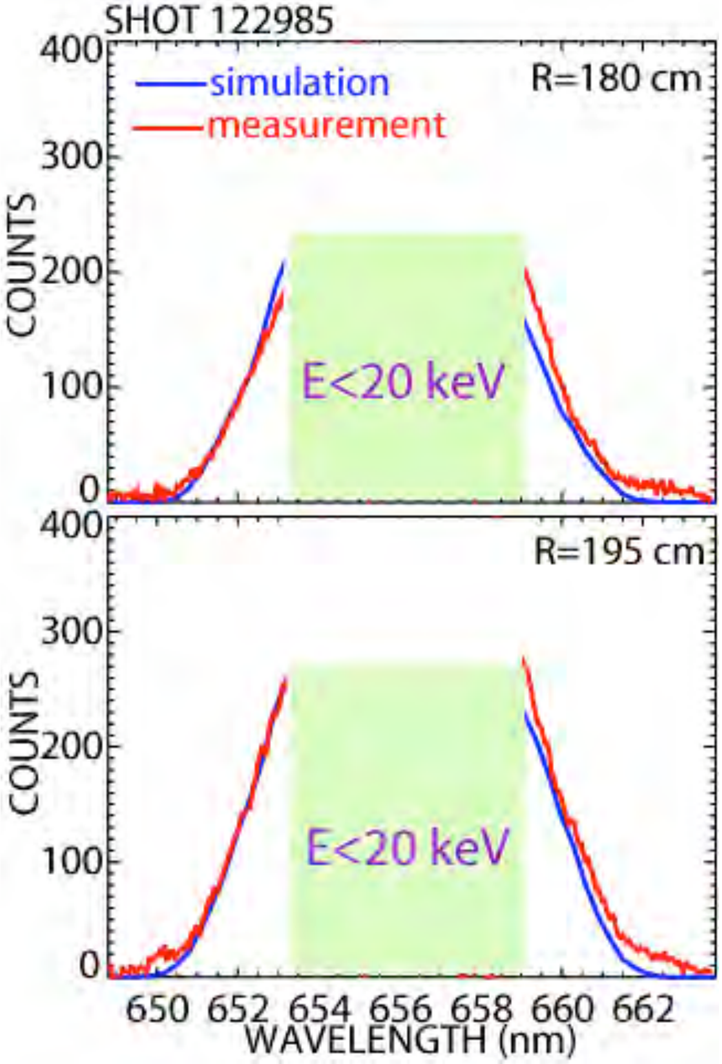
* A. Pankin, et al., *Comp. Phys. Comm.* **159** (2004) 157.

** W.W. Heidbrink, et al., *PPCF* **46**, 1855 (2004).

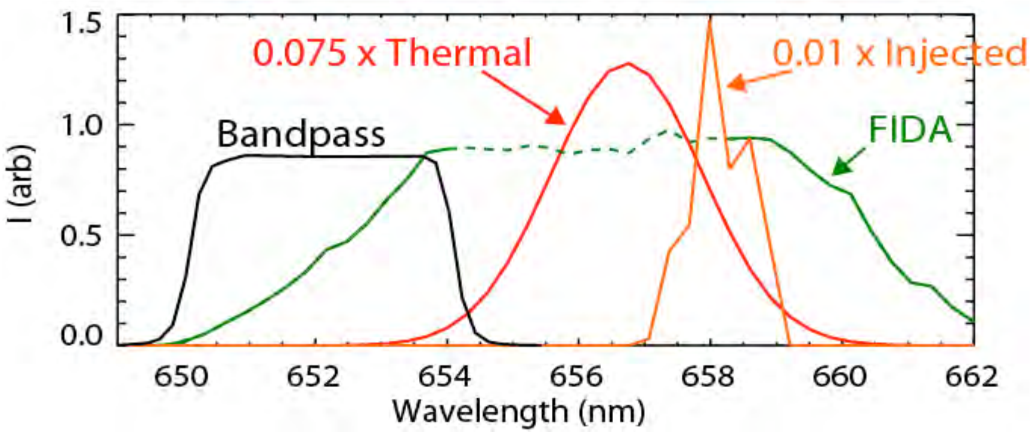
Signals agree with classical theory in MHD-quiescent, low-temperature plasmas

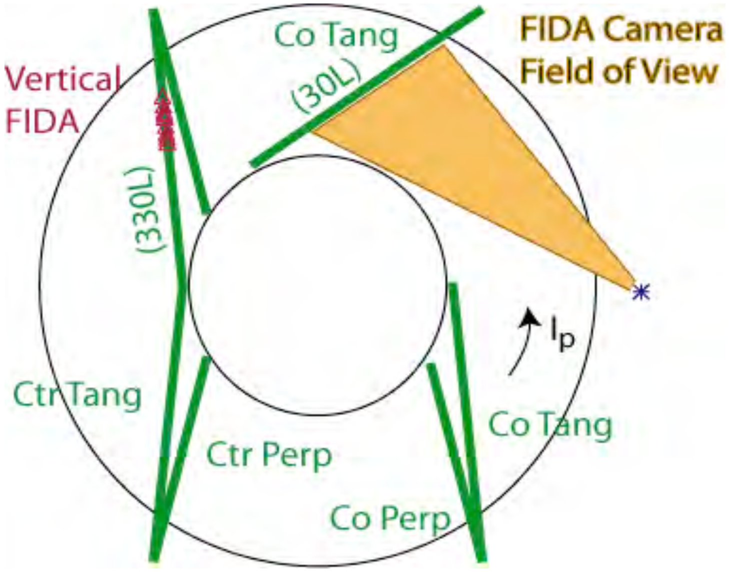
- Studied quiet plasmas first where theoretical fast-ion distribution function is known
- Spectral shape & magnitude agree with theory
- Relative changes in spatial profile agree with theory
- Dependence on injection energy, injection angle, viewing angle, beam power, T_e, & n_e all make sense
- Consistent with neutrons & NPA

Luo, Phys. Pl. 14 (2007) 112503.



FIDA imaging: Put bandpass filter in front of a camera



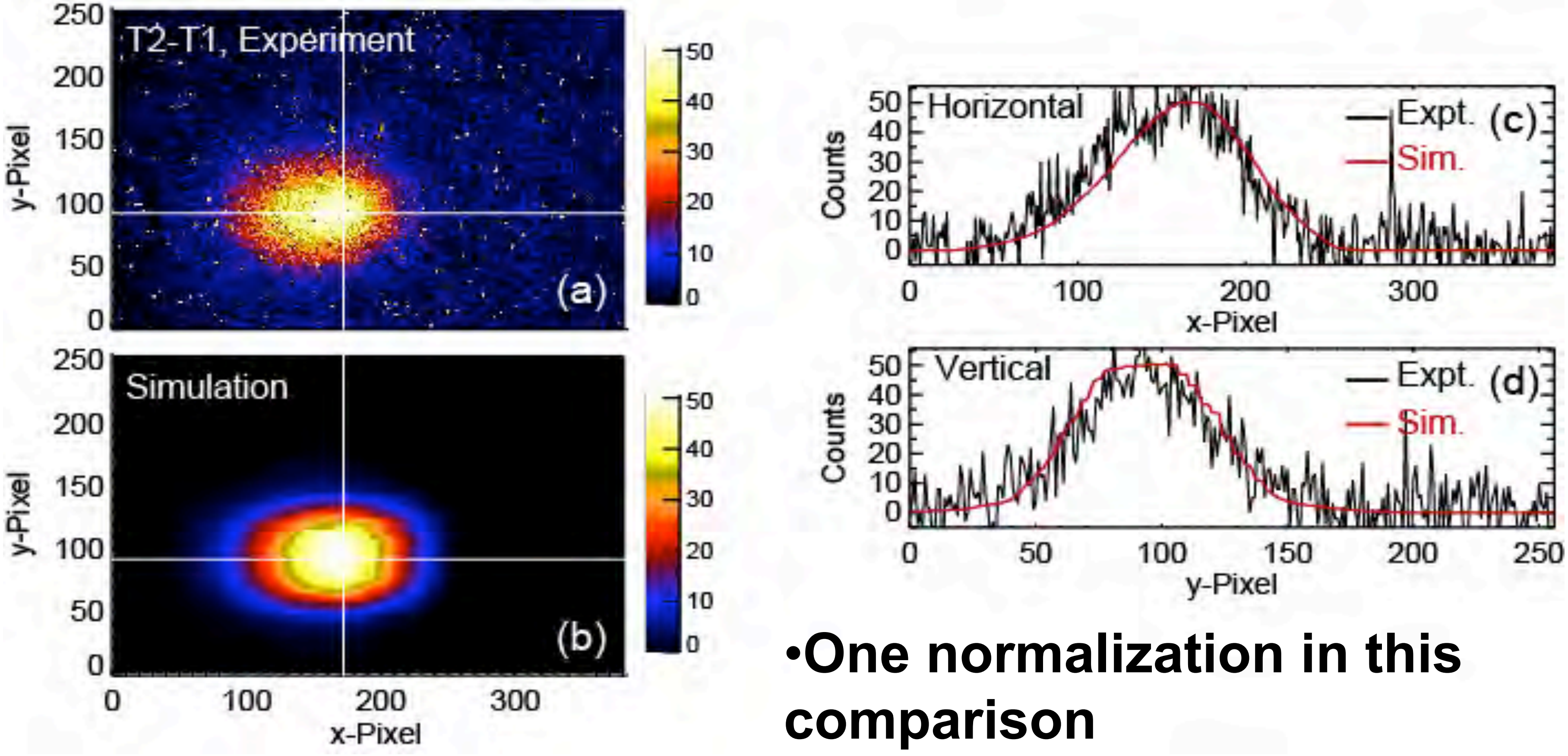


- Oppositely directed fast ions from counter beam produces blue-shifted light (accepted by filter)

- “Imaging” neutral beam produces red-shifted light (filtered out)

Van Zeeland, PPCF 51(2009) 055001.

FIDA image agrees with theory



Van Zeeland, PPCF 51(2009) 055001.

- **One normalization in this comparison**
- **Image taken immediately after counter beam turns off**
- **Time evolution agrees too**

Outline

1) Orbit stochasticity

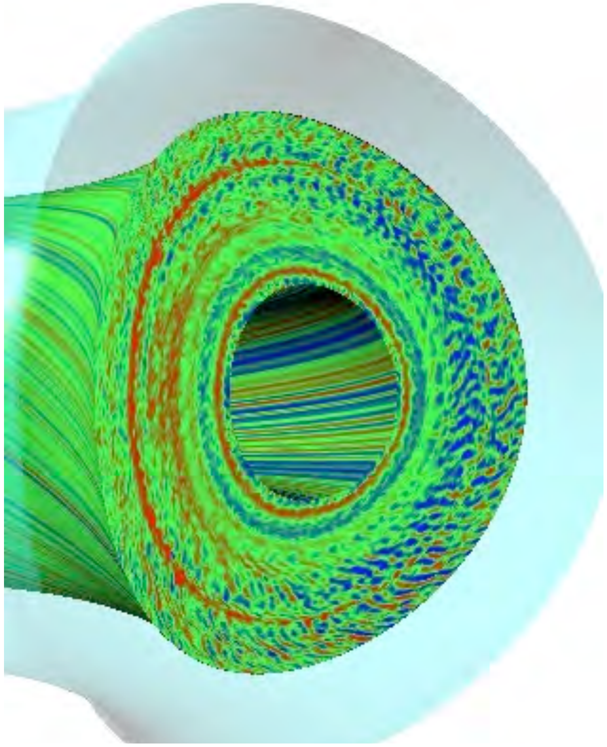
Fast-ion D-alpha (FIDA) diagnostic

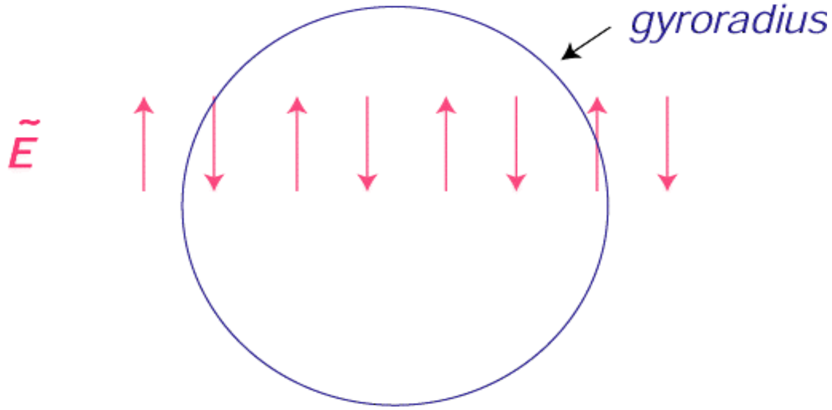
2) Drift-wave turbulence

3) Many small-amplitude Alfvén modes

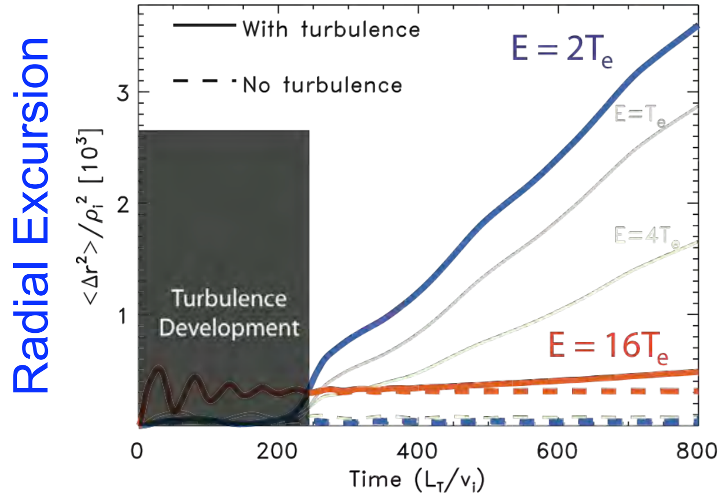
Phase averaging over turbulence reduces fast-ion transport

- **Drift wave turbulence**
  - ion-temperature gradient (ITG) mode
  - long wavelength ($k_\perp \rho_i < 1$)
  - Decorrelation length scales with ρ_s or ρ_I ~ sqrt(T)
- **Large fast-ion orbit**
  - Both gyro-motion and drift motion
  - Orbit size scales with sqrt(E_{EP})
- **Orbit averages over smaller-scale fluctuations**
  - (orbit size):(decorrelation length)
  - Scaling parameter: T/E_{EP}





Basic mechanism well established but theorists debate details



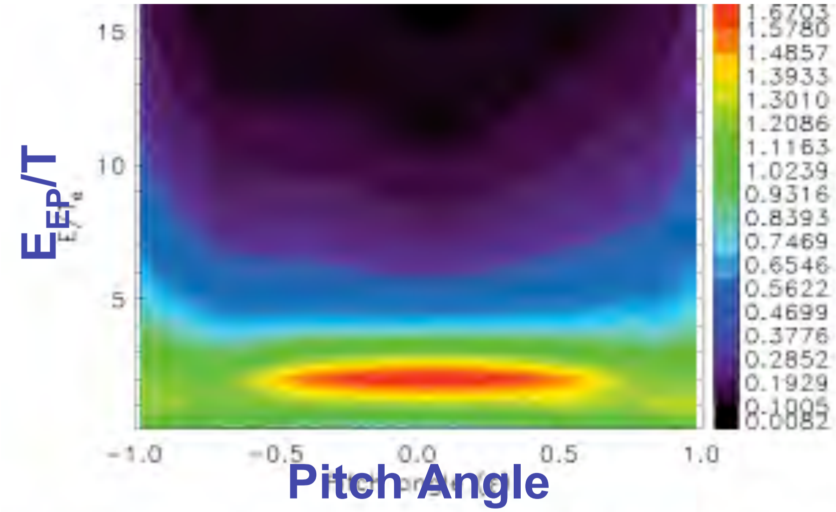


FIG. 3 (color). Diffusivity D=D$_I$ as a function of particle energy E=T$_e$ and pitch angle ξ.

W. Zhang, Phys. Rev. Lett. 101 (2008) 095001.

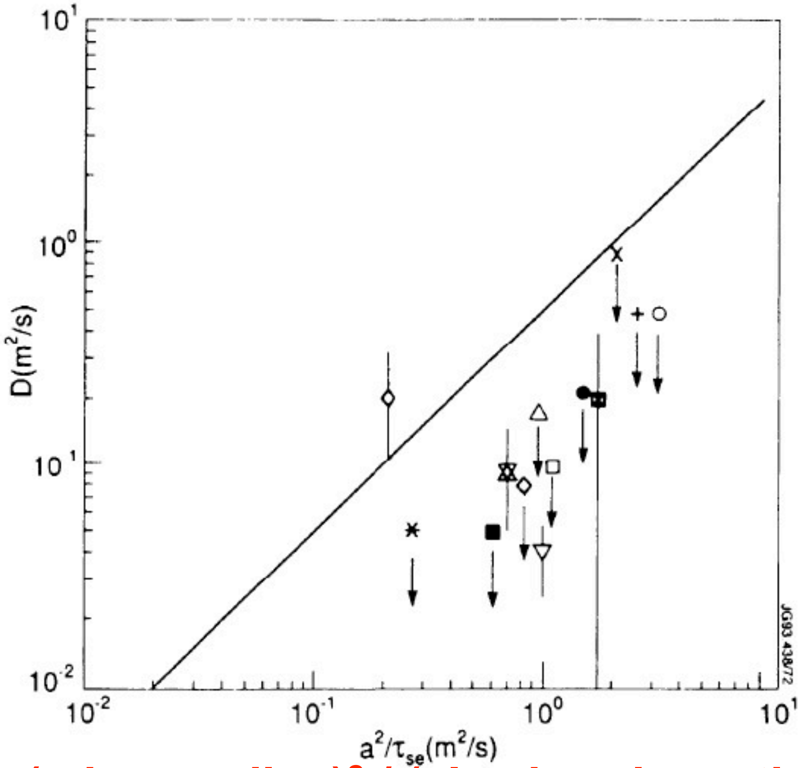
- **First simulation in 1979! Gyro-phase averaging scales as:** $J_o(k_\theta \rho_f)$

Many recent simulations

- **Estrada-Mila, Candy, Waltz**
- **Hauff, Jenko *et al.***
- **Angioni & Peters**
- **Zhang, Lin, Chen**
- **Albergante**

- **Electrostatic transport scales with T/E_{EP} (to some power)**
- **$D_B(r)=f[T(r)/E_{EP}]\ D_i(r)$**

Measured fast-ion transport for E/T >> 10 is very small



Effective Diffusion

(minor radius)^2 / (slowing-down time)

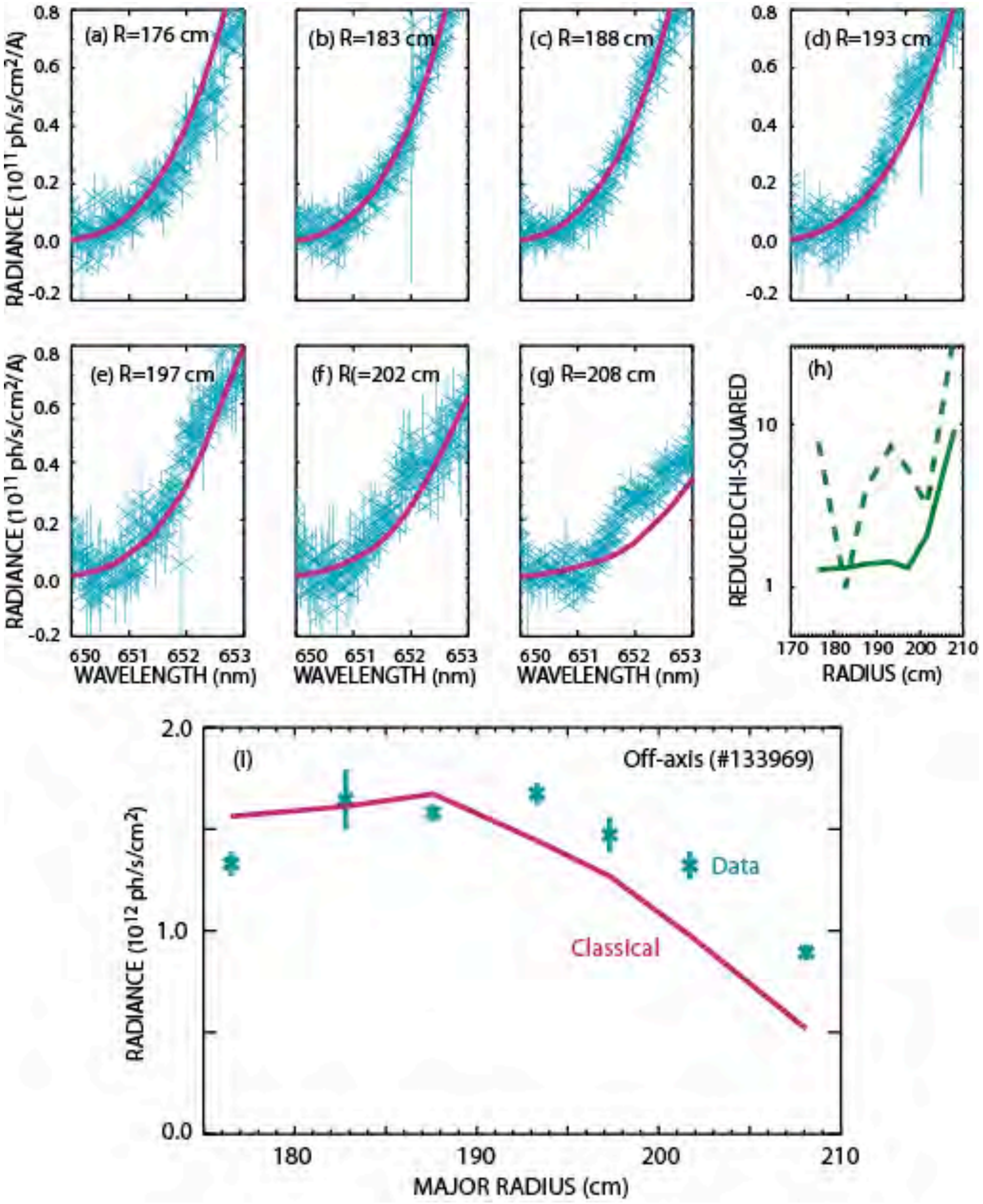
Heidbrink, Nucl. Fusion 34 (1994).

- Cases with MHD or fast-ion driven instabilities excluded
- Reconfirmed in many recent measurements but three anomalies reported

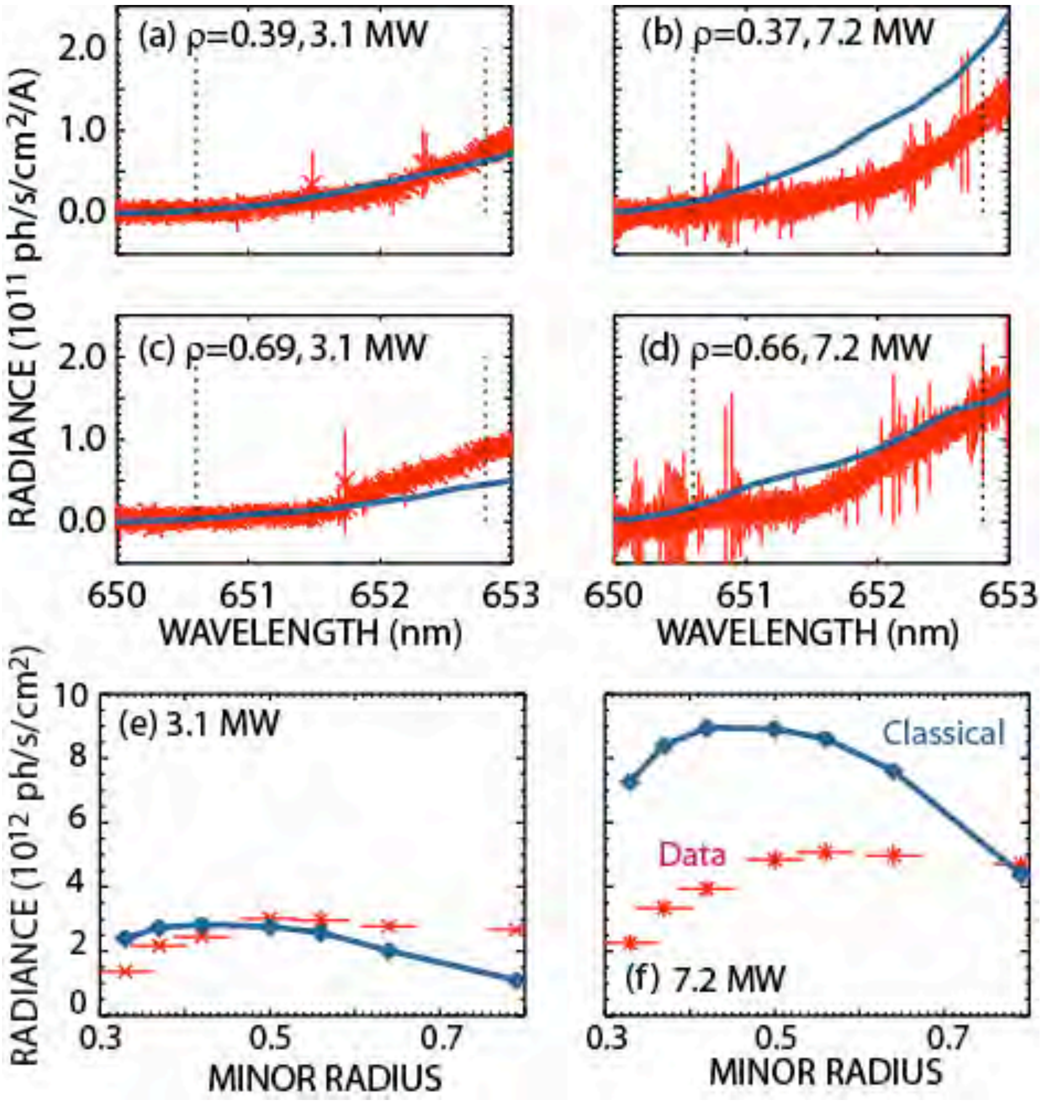
FIDA spectral shape & profile often agree with classical theory

- Vertical FIDA is absolutely calibrated--no free parameters in this comparison

- This case: relatively low temperature L-mode plasma



Large discrepancies are observed in higher-temperature plasmas

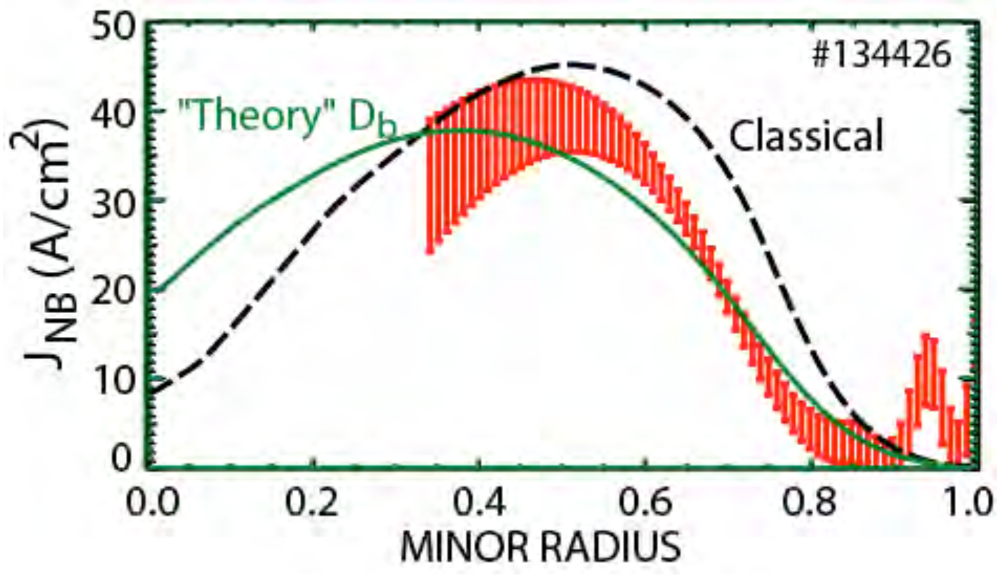


Heidbrink, PRL 103 (2009) in press.

- No MHD or fast-ion driven modes
- Co-tangential off-axis injection
- Low power case in good agreement at small minor radius but discrepant at low Doppler shift (low energy)
- High power case discrepant everywhere

The measured NBCD shows similar discrepancies

Highest Power (7.2 MW) case

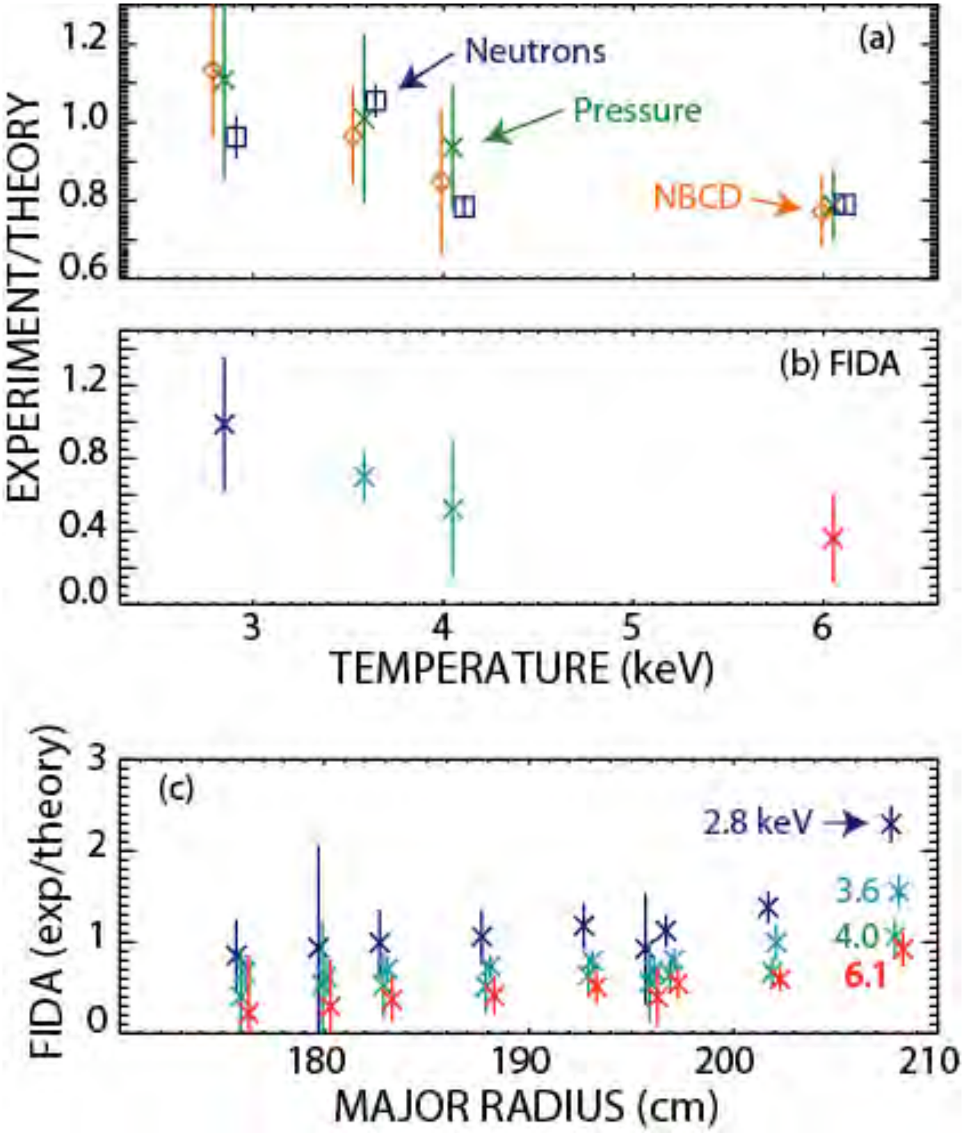


J.M. Park, Phys. Pl. 16 (2009) ???.

- Profiles based on MSE
- Classical prediction agrees with experiment for low-power shots
- Fast-ion diffusion prediction (discussed below) in better agreement

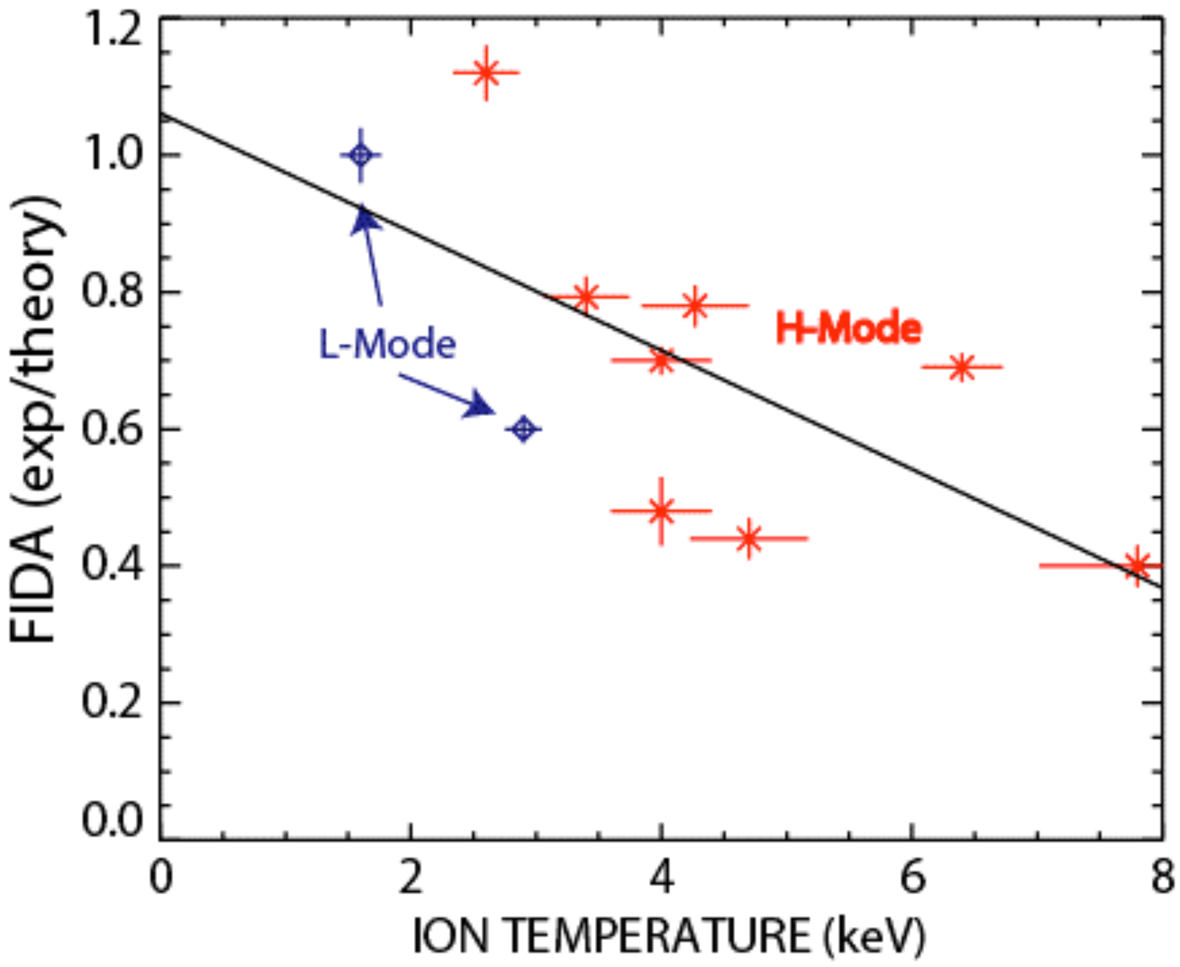
The deviations are greater in higher temperature shots

- Four NBCD shots with increasing co-tangential power
- Discrepancy increases for all four fast-ion diagnostics with increasing power
- Discrepancy is largest for FIDA (more sensitive to low energies)



Heidbrink, PPCF 51 (2009) in press

The discrepancy scales with temperature as expected for transport by microturbulence



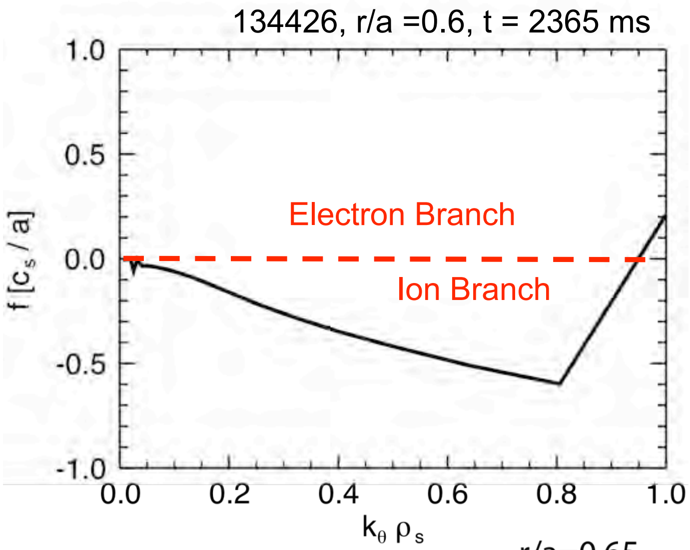
- **Similar scaling with T_e**

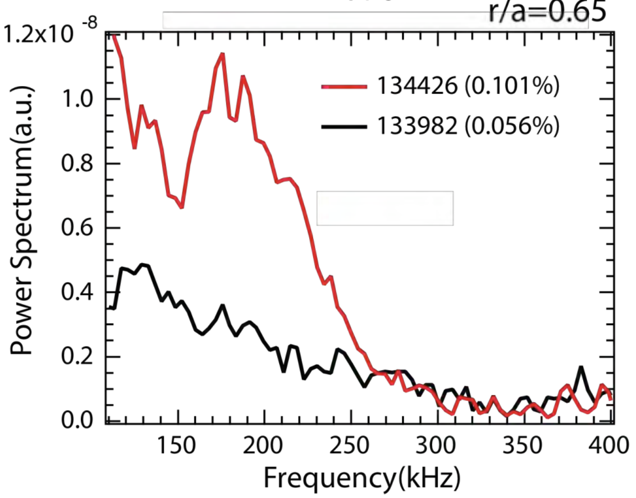
Heidbrink, PPCF 51 (2009) in press

ITG Turbulence is the Dominant Mode During the Experiment

- **Trapped Gyro-Landau Fluid (TGLF) code**[*]
  - Solves for linear eigenmodes
    - electron/ion temperature gradient modes (ETG, ITG)
    - trapped electron/ion modes (TEM, TIM)
    - kinetic ballooning modes (KB)
  - Identifies the dominant mode to reside within the ion branch

- **Beam Emission Spectroscopy**
  - shifted plasmas limit resolution
  - fluctuations consistent with long wavelength ITG activity ($k_\perp \rho_i < 1$)





Heidbrink, PRL 103 (2009) in press.

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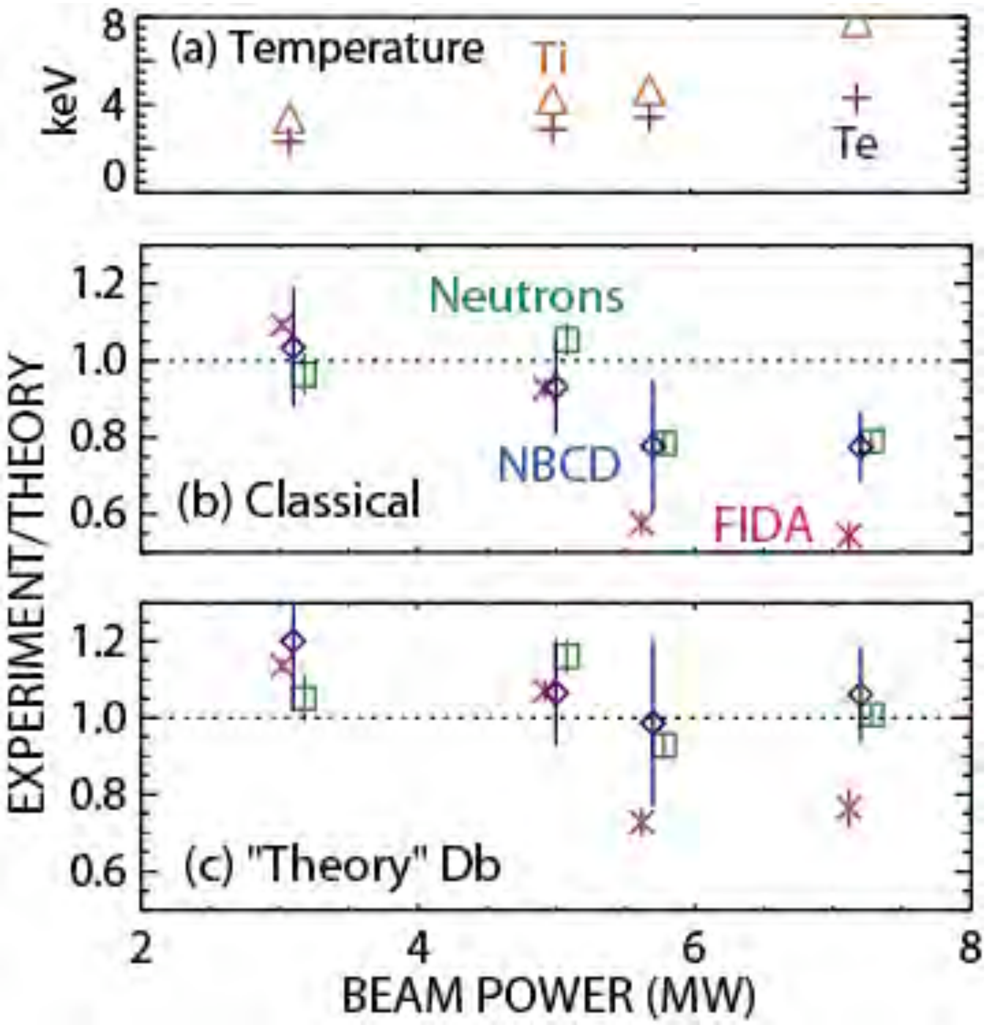
[*] **http://fusion.gat.com/theory/TGLF**

Theory-based estimate is right magnitude



- Approximate modeling using *ad hoc* beam-ion diffusion in TRANSP
- Neutron & NBCD data are consistent with prediction
- FIDA is better but still off
- FIDA is more sensitive to low energies than neutrons or NBCD

Heidbrink, PRL 103 (2009) in press.

Conclusions from Microturbulence Study

- Discrepancies larger at small Doppler shift
- Discrepancies increase with temperature
- Discrepancies are most apparent at large radii where χ_i is larger
- Anomalies affect all injection angles
- Neutrons, FIDA, and NBCD see similar anomalies
- Magnitude of predicted transport from microturbulence about right

◊ Microturbulence causes fast-ion transport

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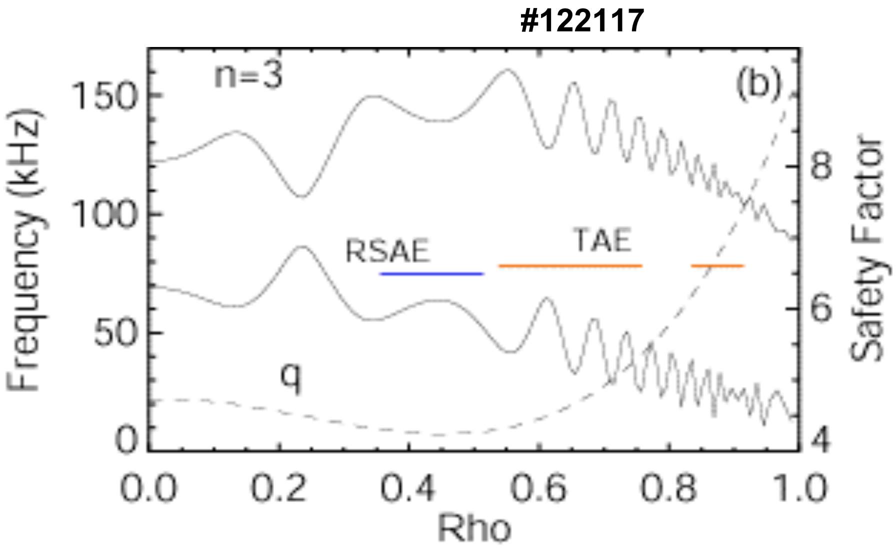
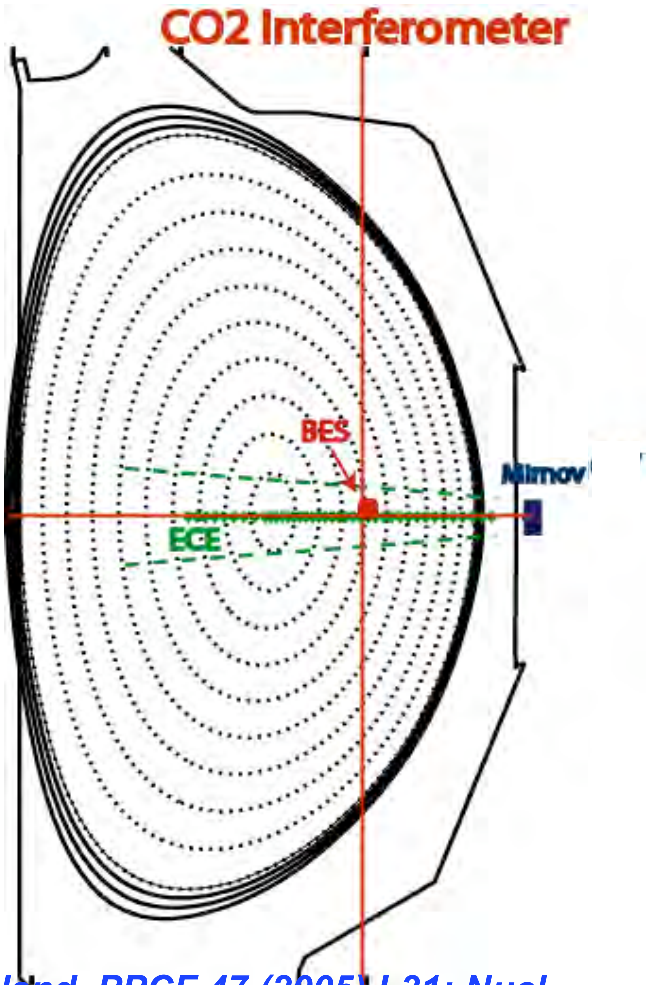
Beam ions readily drive Alfvén instabilities in low density, reversed shear plasmas



Van Zeeland PoP 14 (2007) 056102.

- •Reversed shear with early beam injection (80 keV D^0 co-injection)
- •Modest density ◊ large beam beta to drive modes
- •Fast-ion speed > $v_A/3$ ◊ circulating fast ions resonate with TAEs

Sensitive Diagnostics Measure Fluctuations in n_e, T_e, and B



Van Zeeland, PPCF 47 (2005) L31; Nucl. Fusion 46 (2006) S880; PoP 14 (2007) 056102.

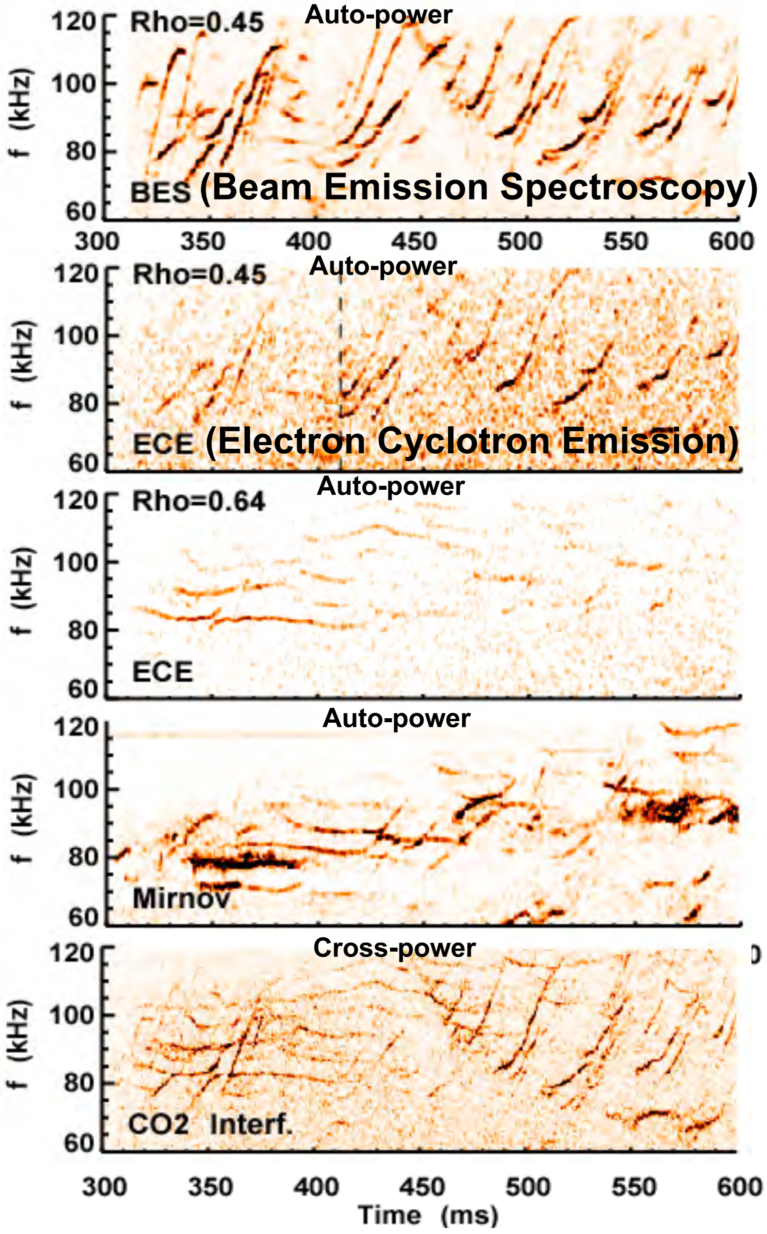
RSAEs dominate

RSAEs dominate

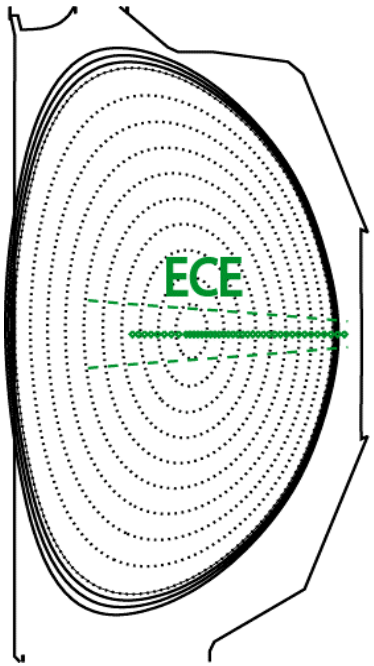
TAEs dominate

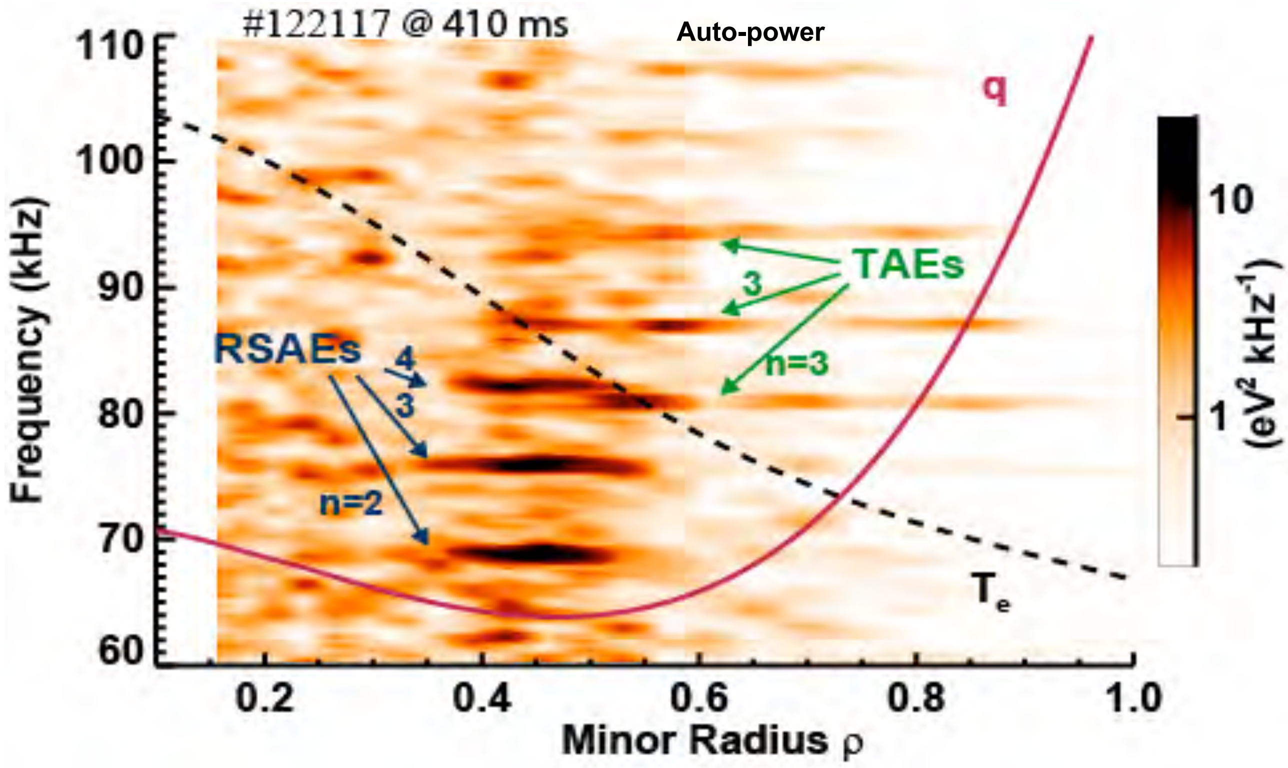
TAEs dominate

TAEs & RSAEs



The Upgraded ECE Diagnostic Measures the Radial Eigenfunction



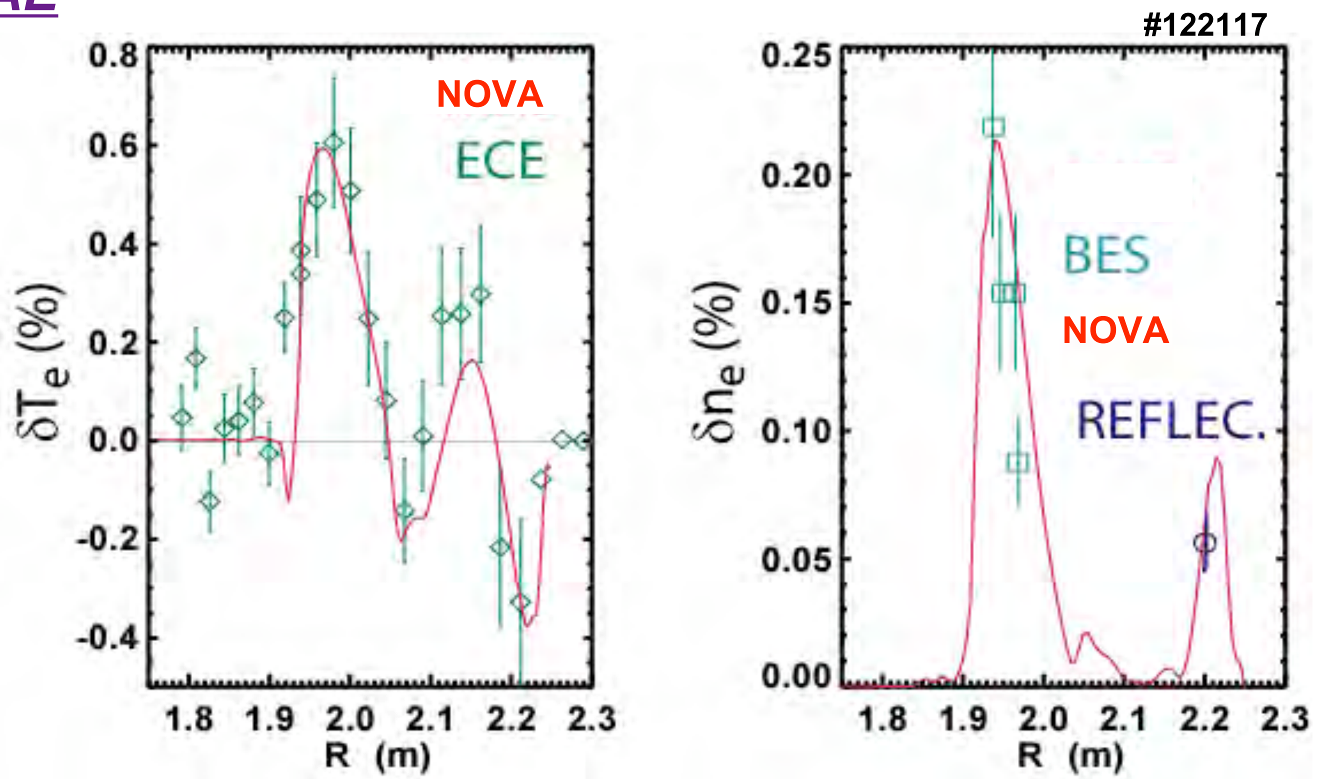


- **RSAEs are localized at q_{min}**
- **TAEs are globally extended**

Van Zeeland, PRL 97 (2006) 135001; PoP 14 (2007) 056102.

The Mode Structure agrees with linear ideal MHD Theory (NOVA code)

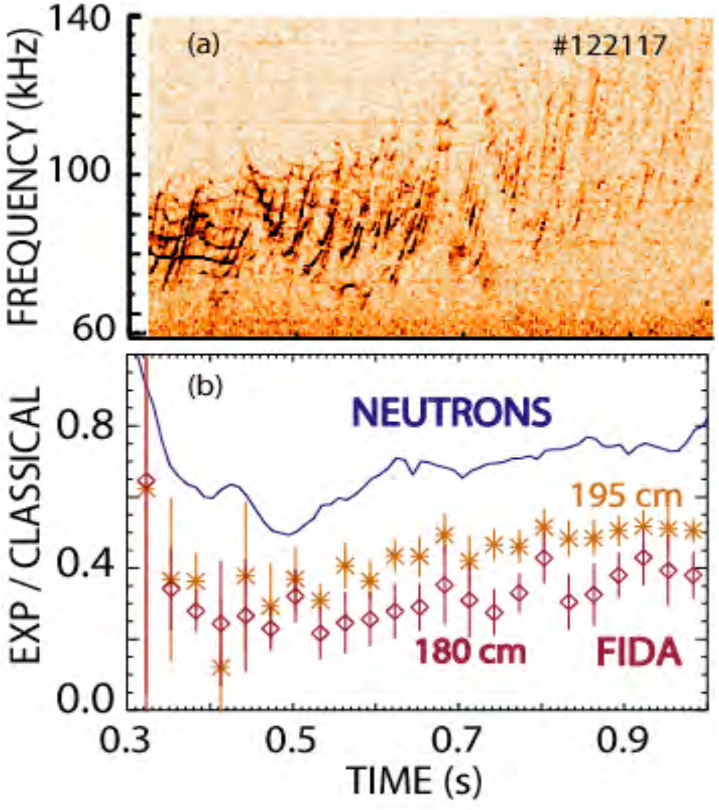
n=3 RSAE



- **The MHD δT_e amplitude is scaled to match the ECE data**
- **No free parameters in the δn_e comparison**
- **The TAE data also agree well**

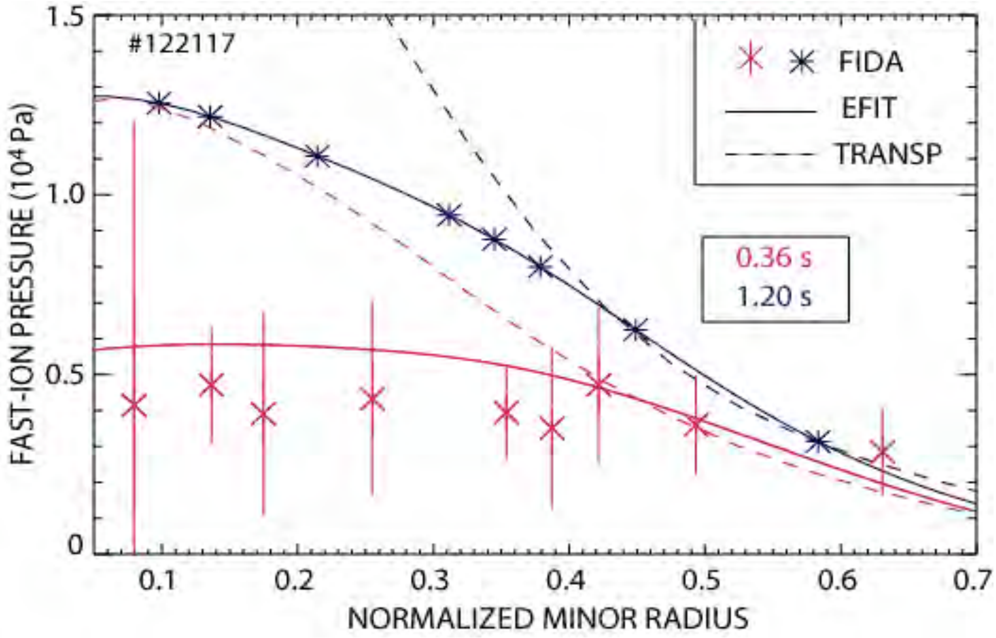
Van Zeeland, PRL 97 (2006) 135001.

Severe Flattening of Fast-ion Profile Measured during Alfven Eigenmodes

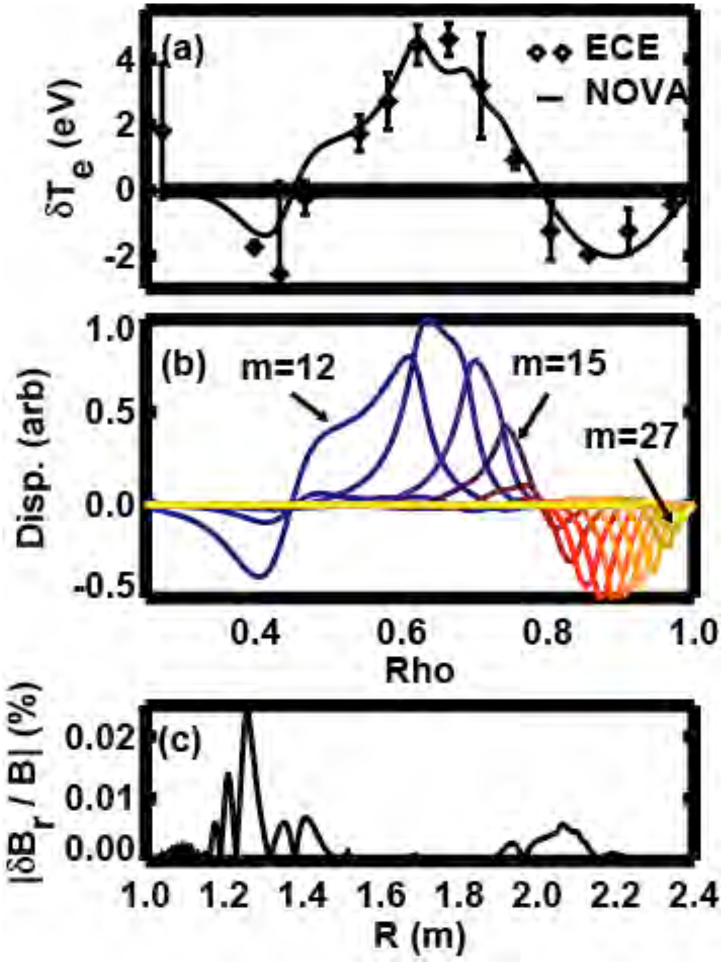


- •Corroborated by neutron, current profile, toroidal rotation, and pressure profile measurements
- •Reduction correlates with mode amplitude

Heidbrink, PRL 99 (2007) 245002; NF 48 (2008) 084001.



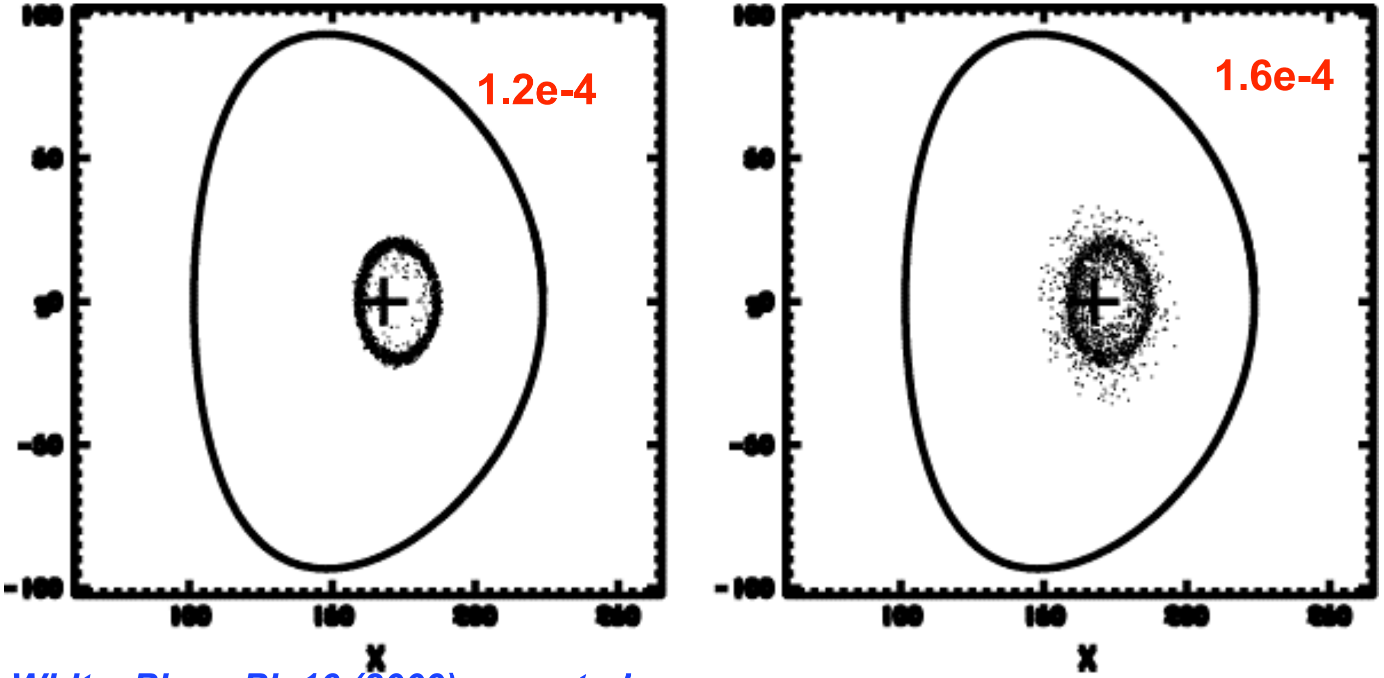
Match measured fluctuations to MHD modes◊ insert fields in orbit following code



White, Phys. Pl. 16 (2009) accepted

- 151 harmonics are generated from NOVA matches to the 11 strongest experimentally measured toroidal modes at a particular time.
- Modes are fairly weak: $\delta B_r/B \sim O(e-4)$

With many modes predict stochasticity at measured mode amplitude



White, Phys. Pl. 16 (2009) accepted

- •Large orbits ◊ each mode has many resonances in phase space
- •Prediction fails for fewer modes
- •Inclusion of inductive electric field and pitch-angle scattering necessary

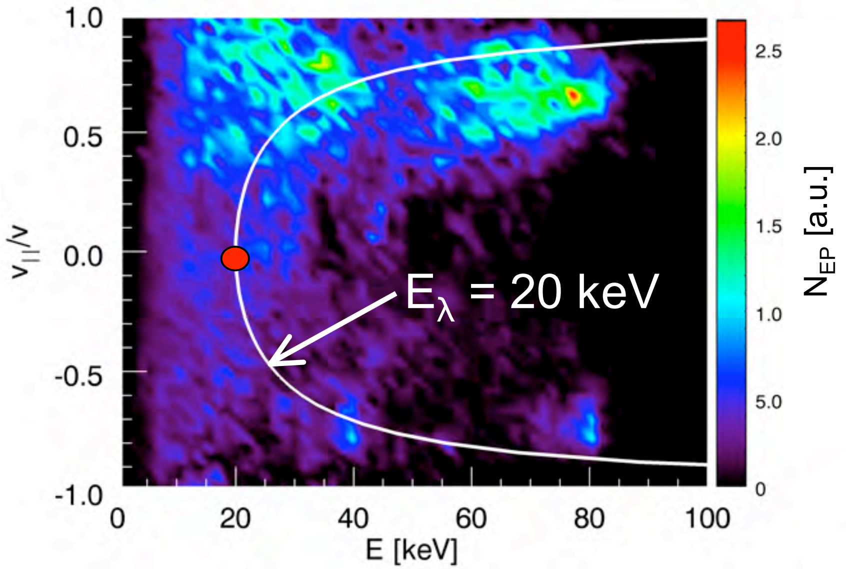
Conclusions

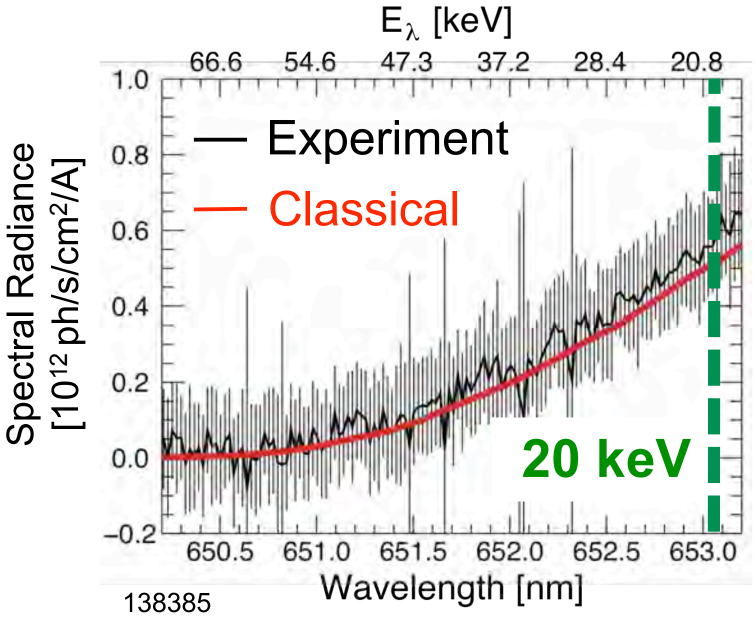
- A large helical field + large orbits ◊ orbit stochasticity
- FIDA is a powerful new diagnostic technique
- Drift waves cause appreciable fast-ion transport when E/T ~ 10
- Many small amplitude Alfvén eigenmodes can cause orbit stochasticity ◊ flat fast-ion profile

Backup slides

FIDA measures one component of the fast-ion velocity

- **Can relate Doppler-shift to equivalent energy of measured component**
- **Additional energy in other components**





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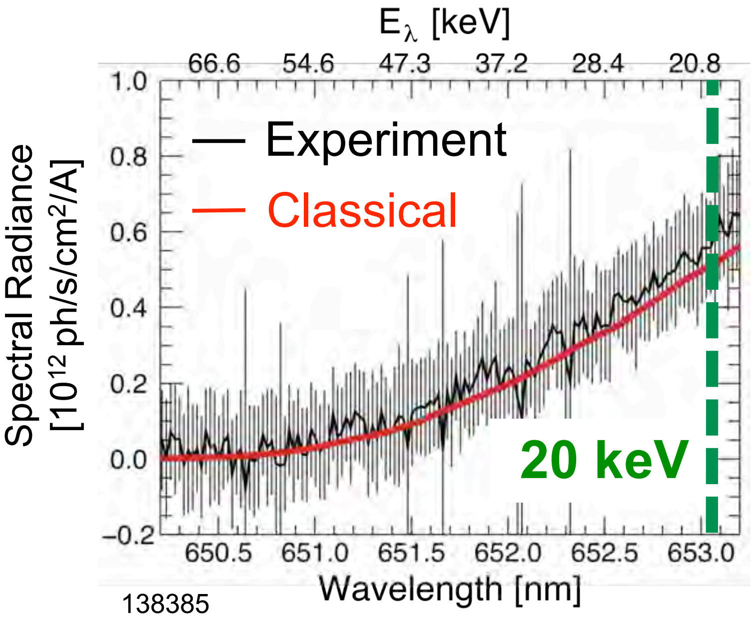

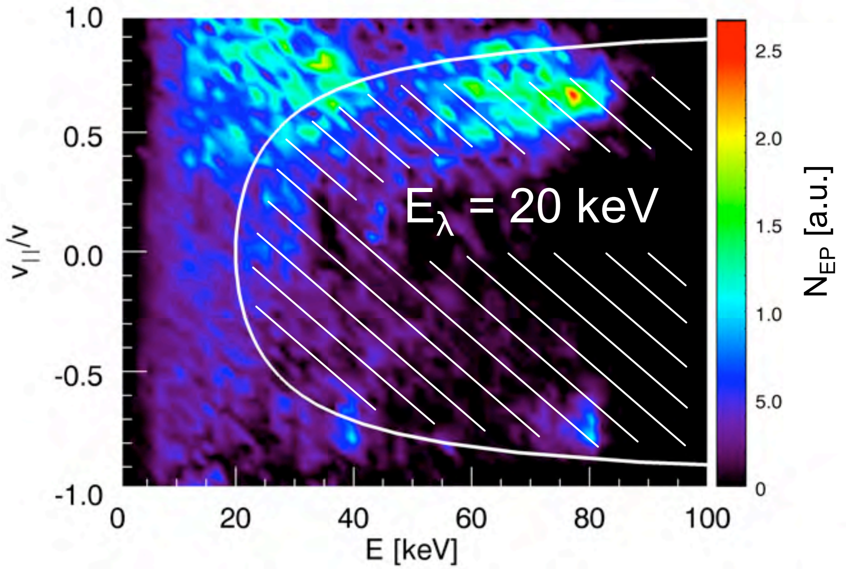

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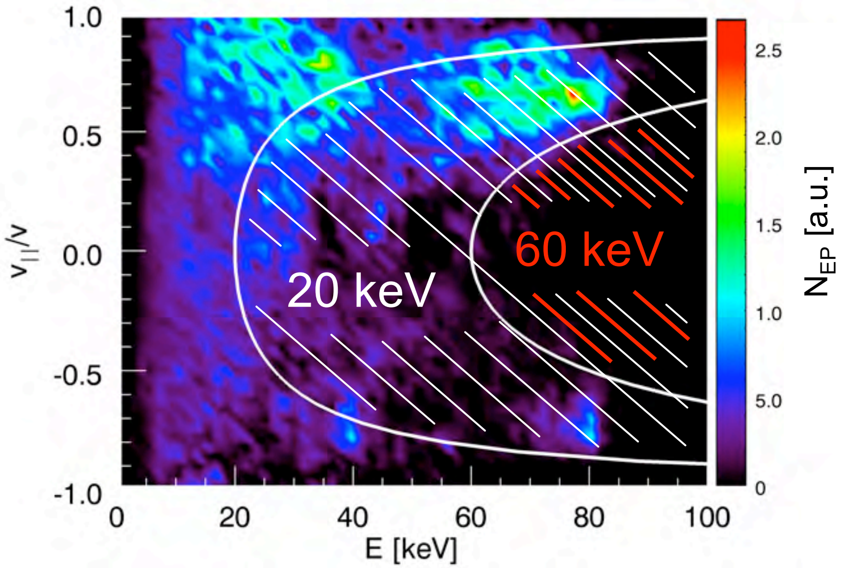

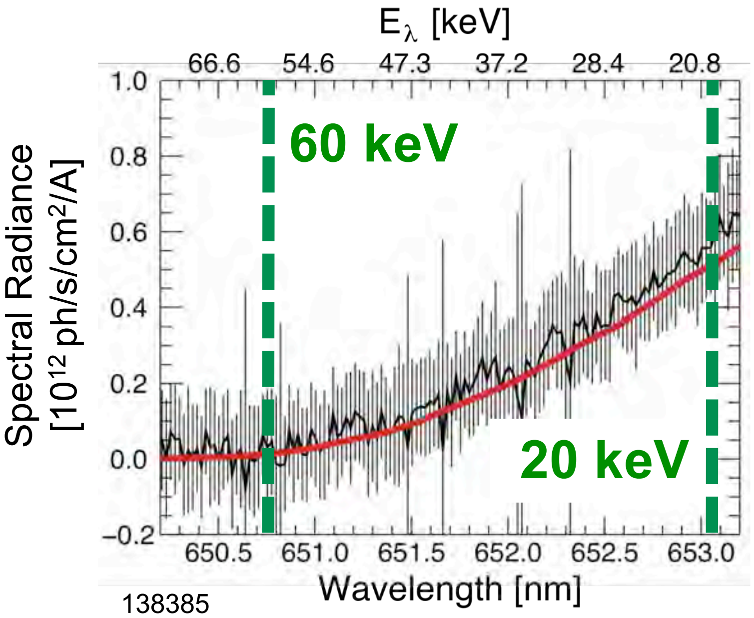

A brief history of FIDA

- **First observation of FIDA light** Heidbrink, PPCF 46 (2004) 1855
- **Background subtraction dominates error** Luo, RSI 78 (2007) 033505
- **Measurements agree with theory in MHD-quiescent plasmas** Luo, PoP 14 (2007) 112503
- **Alfvén eigenmodes flatten profile** Heidbrink, PRL 99 (2007) 245002; NF 48 (2008) 084001
- **Profile of RF-accelerated fast ions** Heidbrink, PPCF 49 (2007) 1457
- **Bandpass filter & PMT for detection at TAE frequency** Podestà, RSI 79 (2008) 10E521; PoP 16 (2009) 056104
- **Bandpass filter & camera for 2D fast-ion image** Van Zeeland, PPCF 51 (2009) 055001
- **Many facilities deploy FIDA diagnostics**