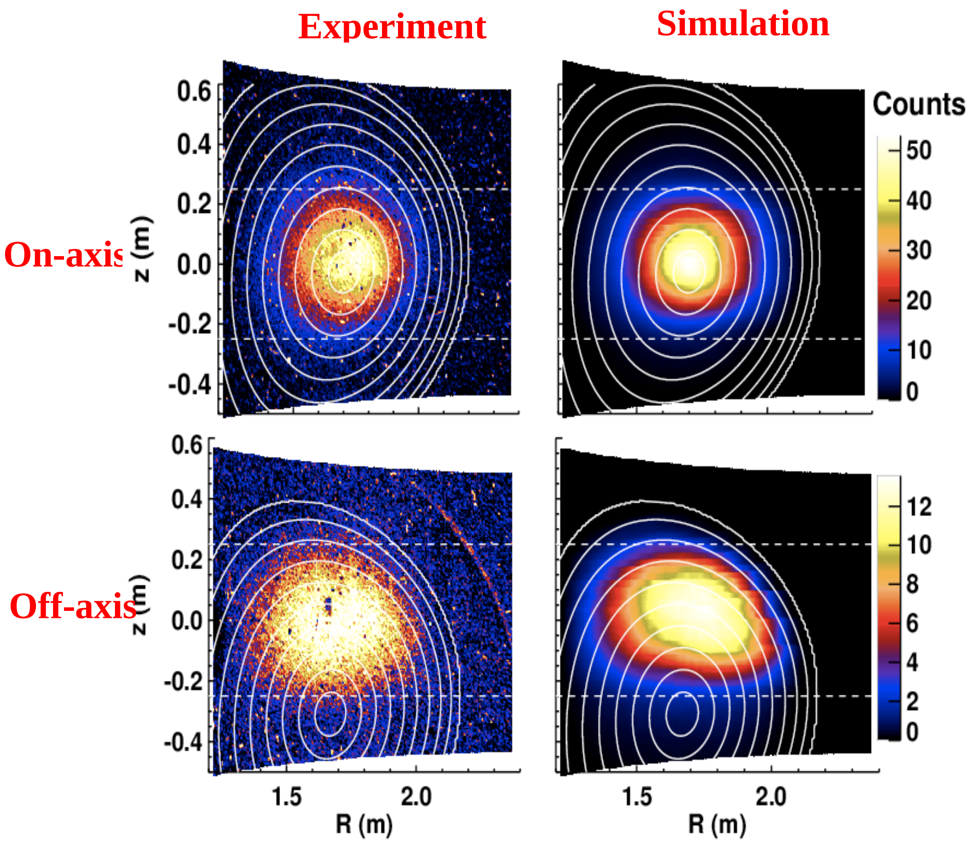
Fast-ion Transport by Microturbulence



W. Heidbrink,
M. Murakami,
J.M. Park,
C. Petty,
M. Van Zeeland, J. Yu

- **No major anomalies vs. beam injection angle** [“Beam-ion Confinement for Different Injection Geometries,” submitted to PPCF (2009)]

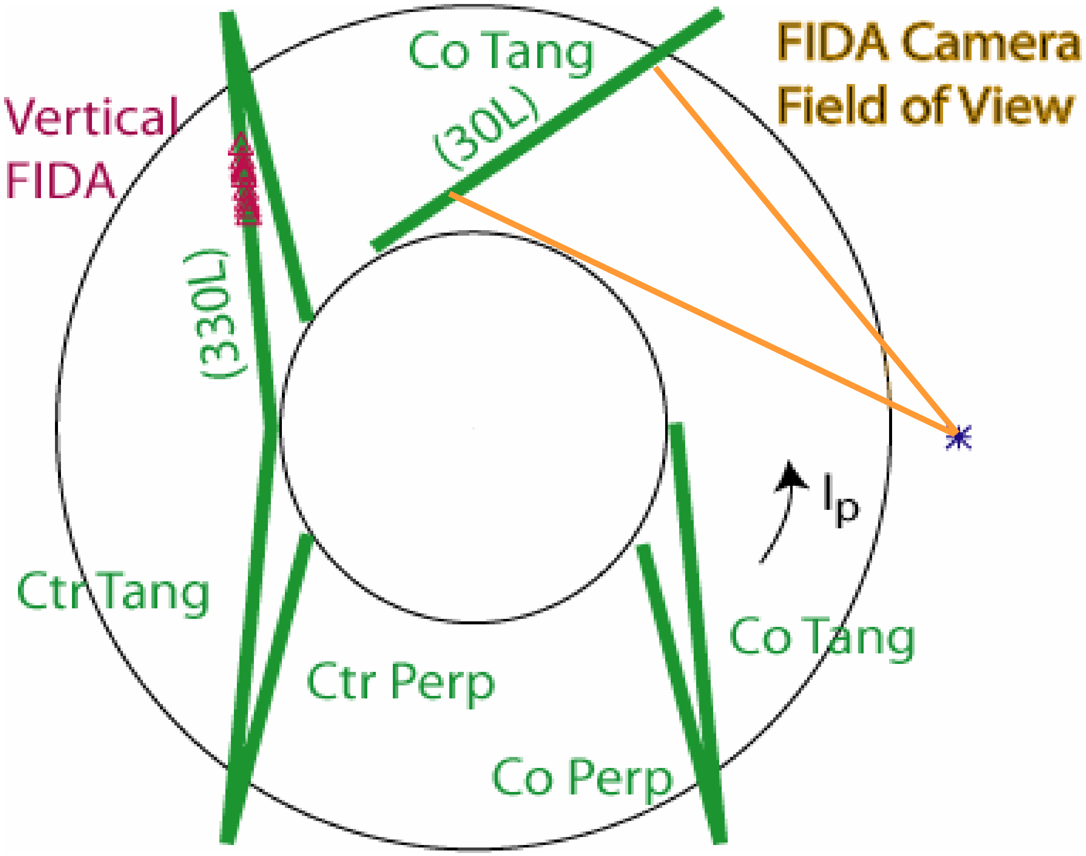
- **Evidence of fast-ion transport by microturbulence** [“Observation of fast-ion transport by microturbulence,” submitted to PRL (2009)]

<u>Related NBCD papers</u> 1) Murakami, Nucl. Fusion 49 (2009) in press; 2) J.M. Park, Phys. Plasmas 16 (2009) submitted

Motivation

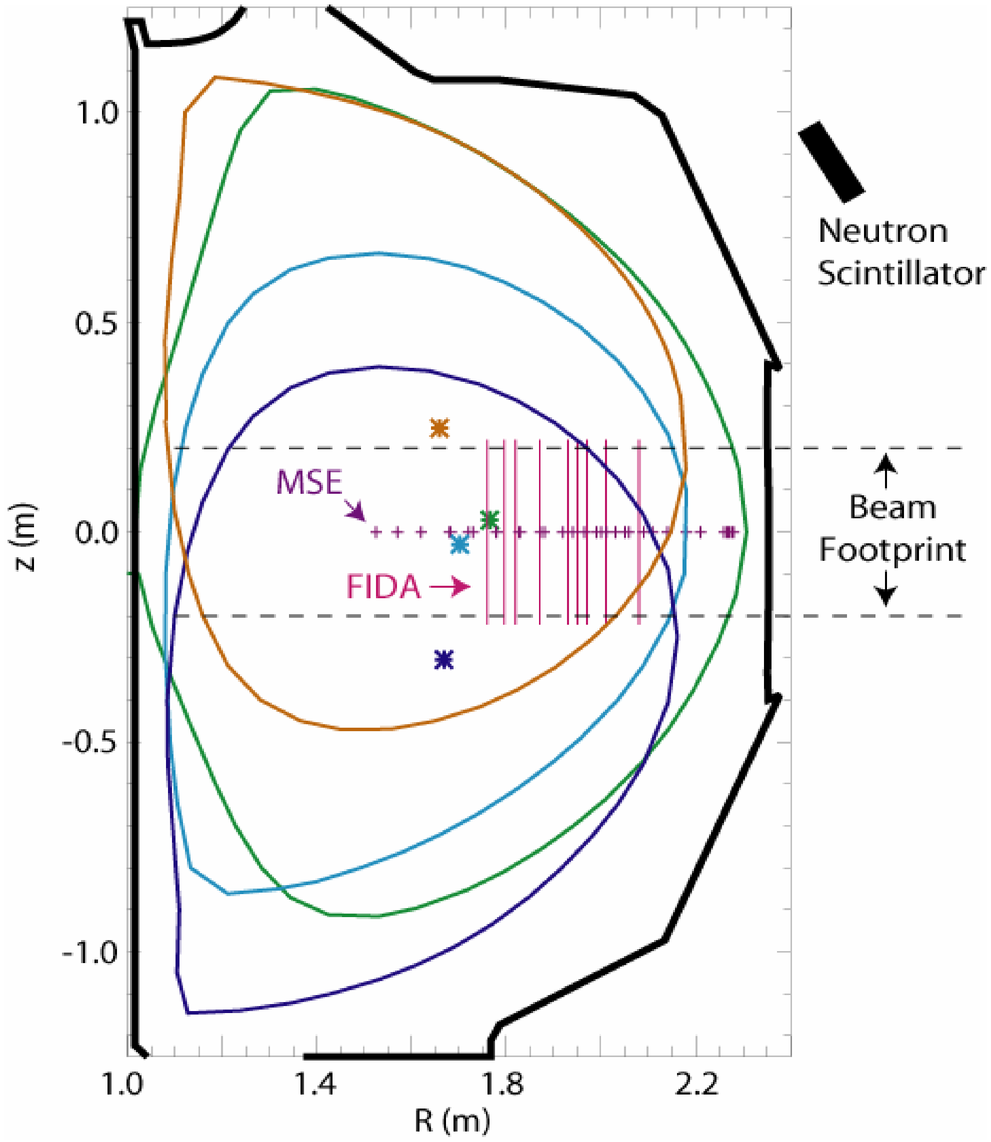
- Neutral beams are the major auxiliary heating system on DIII-D → verify their operation
- Beam ions are a major source of energy, torque, and particles → crucial to understand for transport studies
- Need to know the fast-ion distribution function to understand fast-ion driven instabilities.
- DIII-D is planning to modify a beam to inject off-axis. Will the fast ions drive off-axis current? Or will fast-ion transport fill in the hollow profile?

DIII-D has four different angles of injection



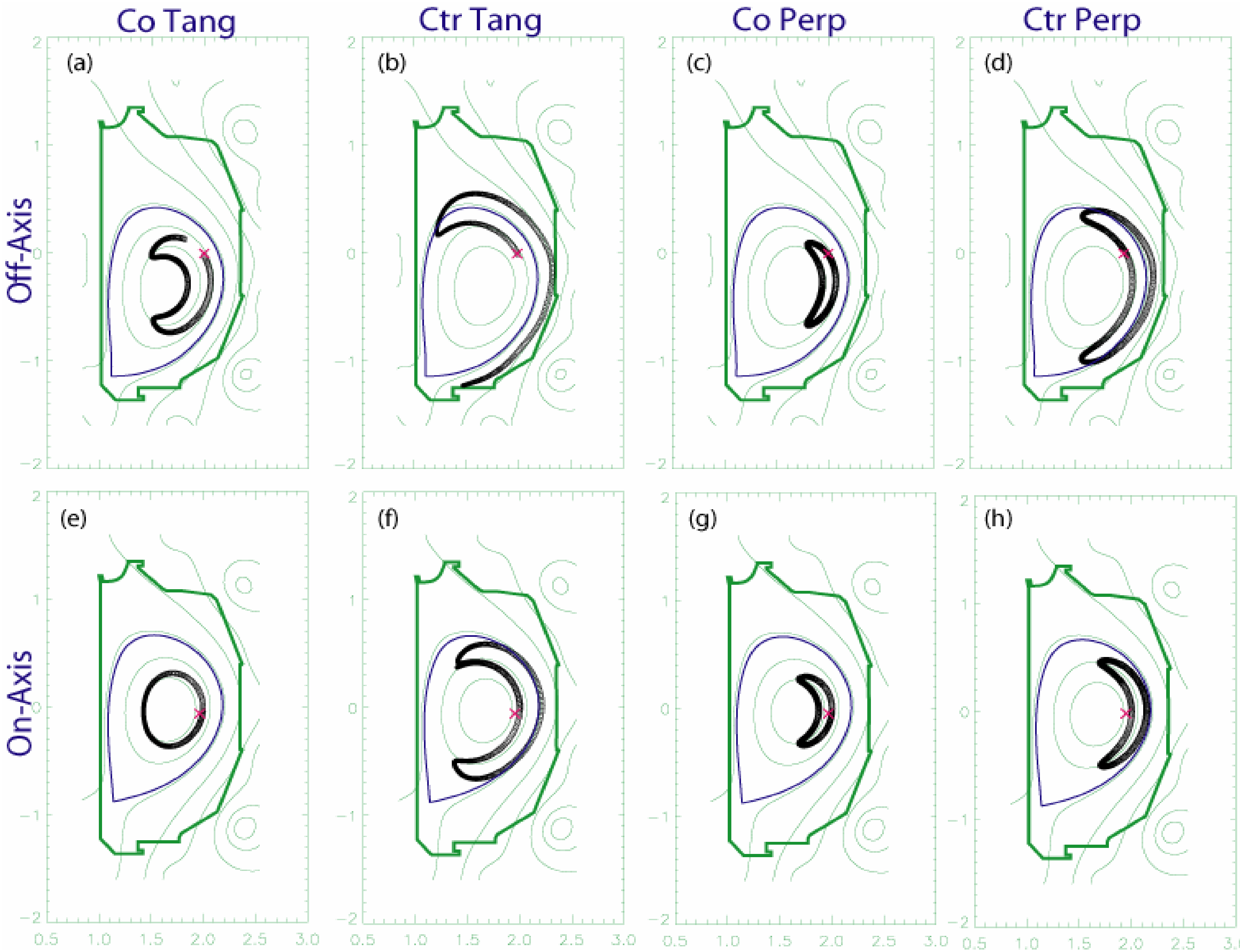
- The beams are also neutral sources for the fast-ion D-alpha (FIDA) diagnostics

Study both on-axis and off-axis injection

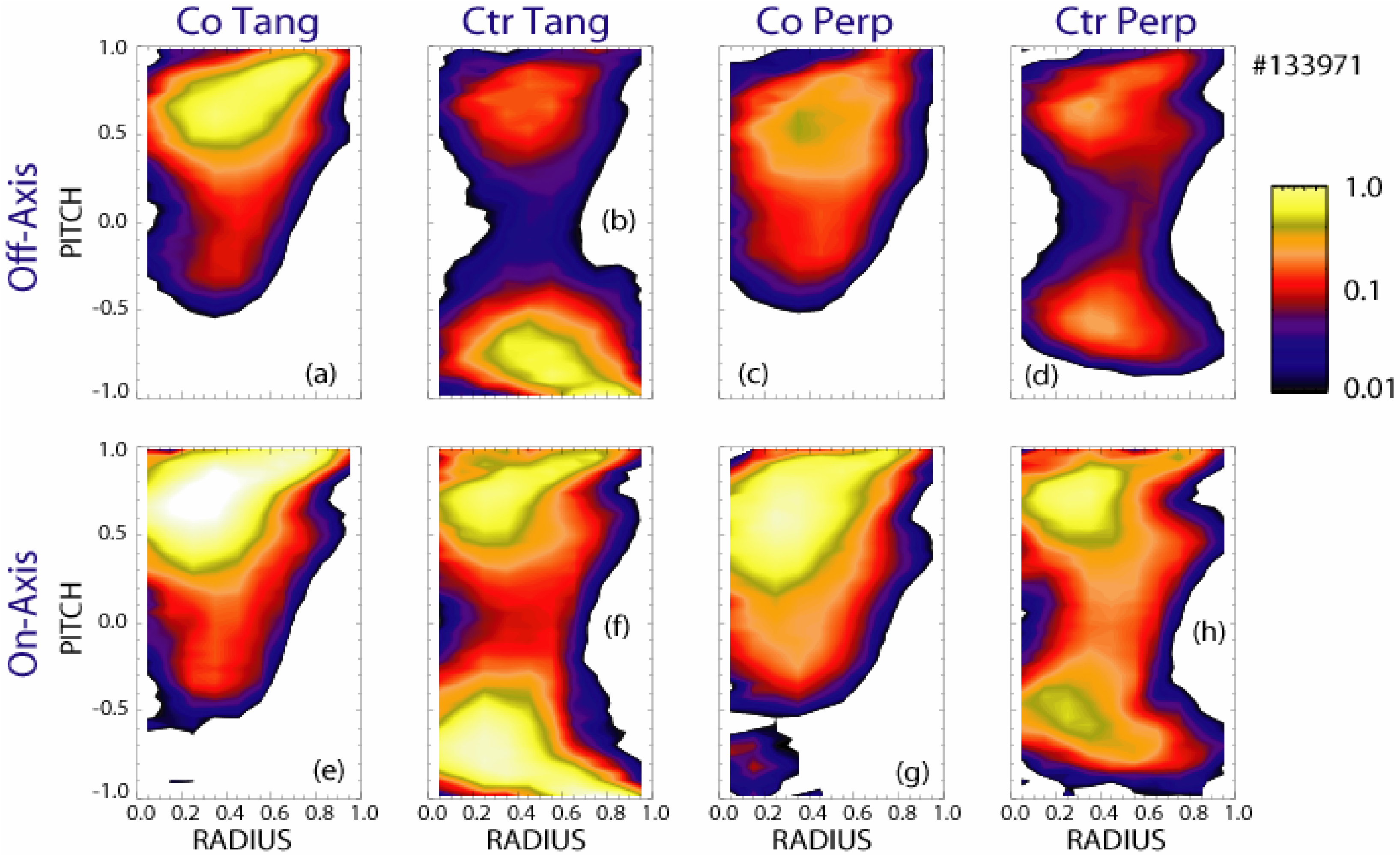


- **FIDA and the neutrons are the main diagnostics**

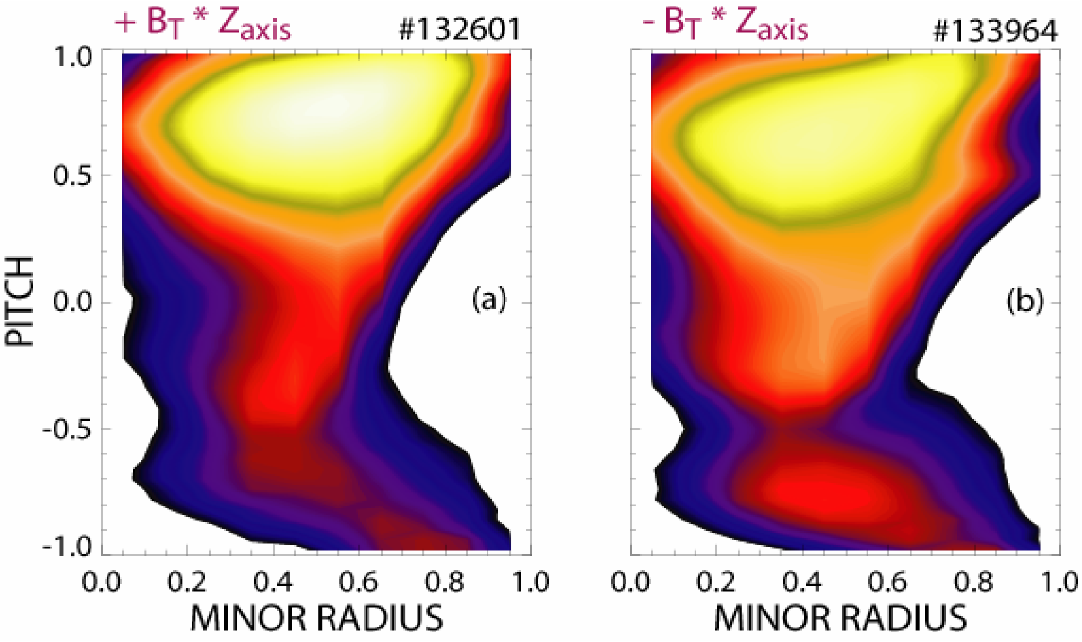
Beam-ion Confinement Depends on Injection Angle



Beam-ion Confinement Depends on Injection Angle

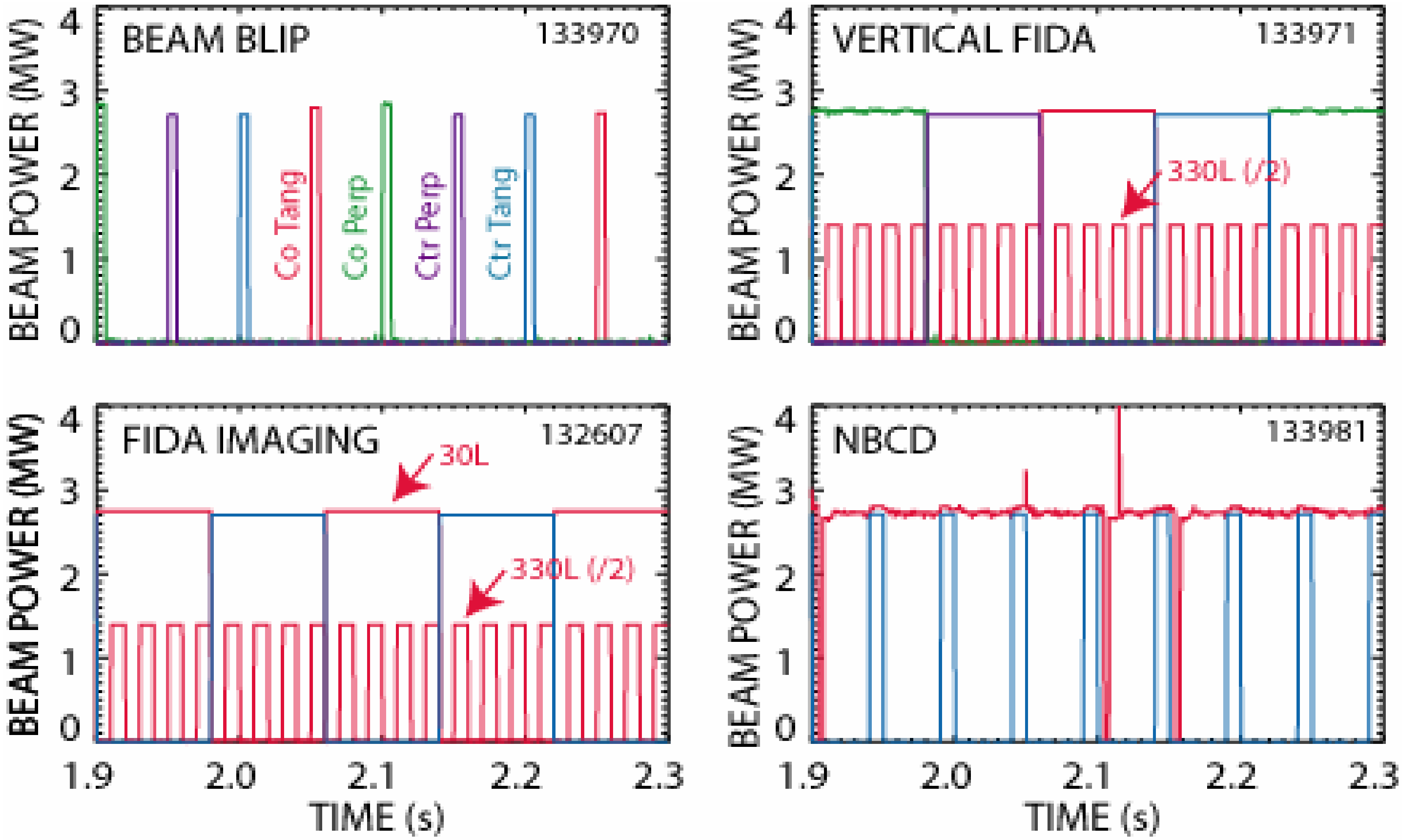


Distribution function depends on the helicity of the magnetic field



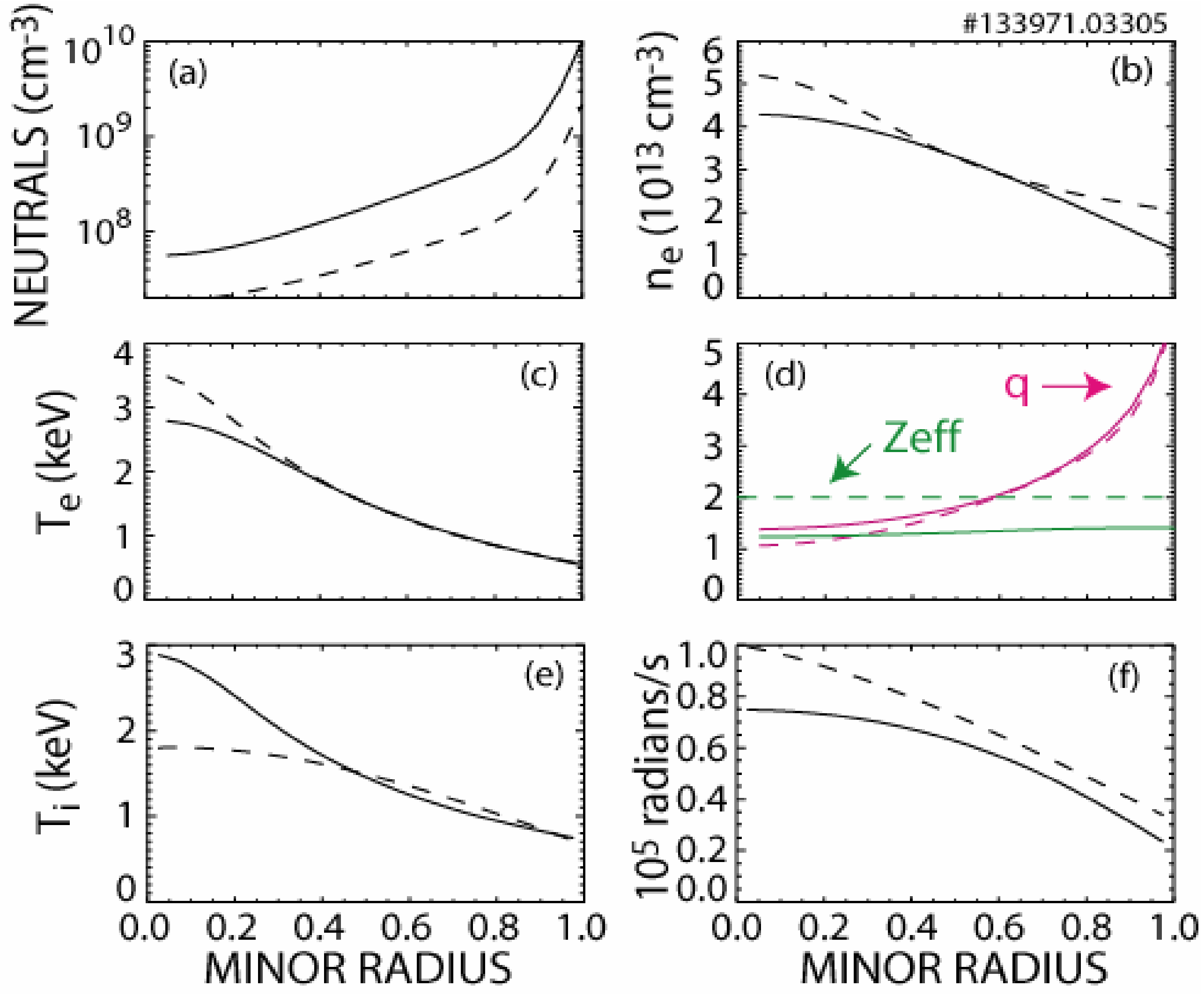
- + Sign has more passing particles & is farther off-axis
- - Sign has more trapped particles & is closer to magnetic axis

Beam modulation patterns optimized for diagnostics

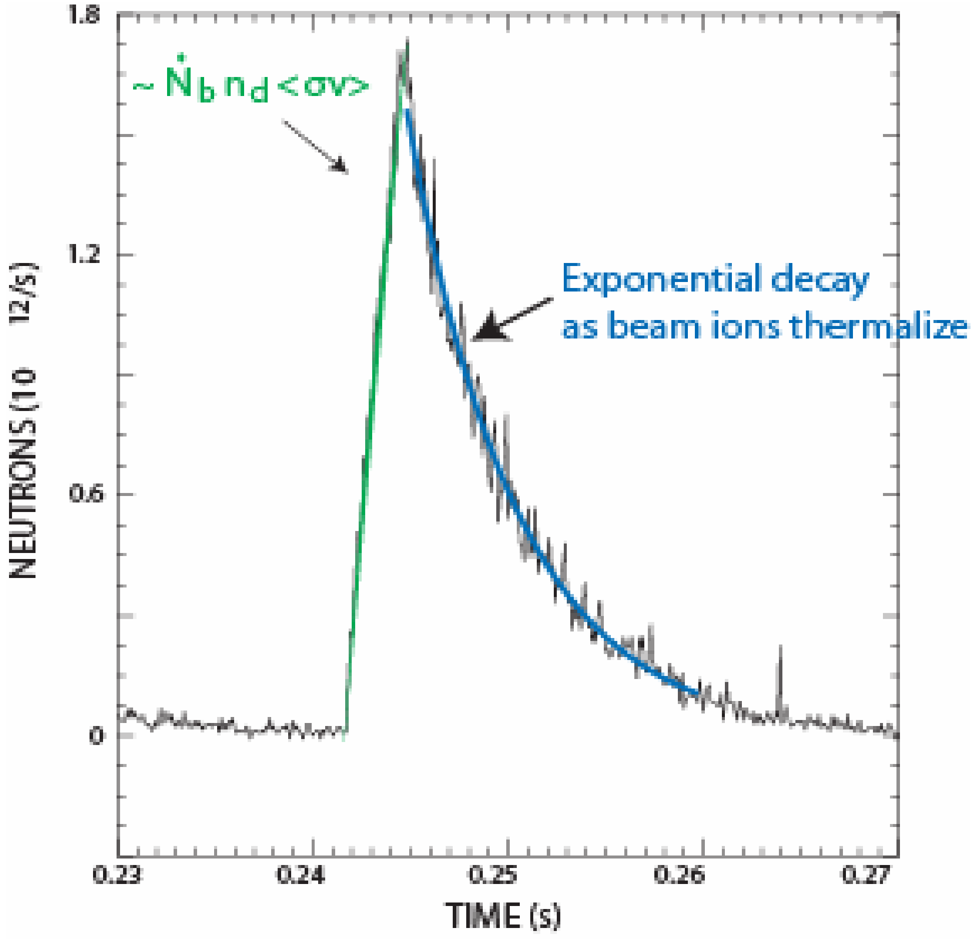


- Plasma conditions approach a steady state

For off-axis injection, profiles have large uncertainties near magnetic axis



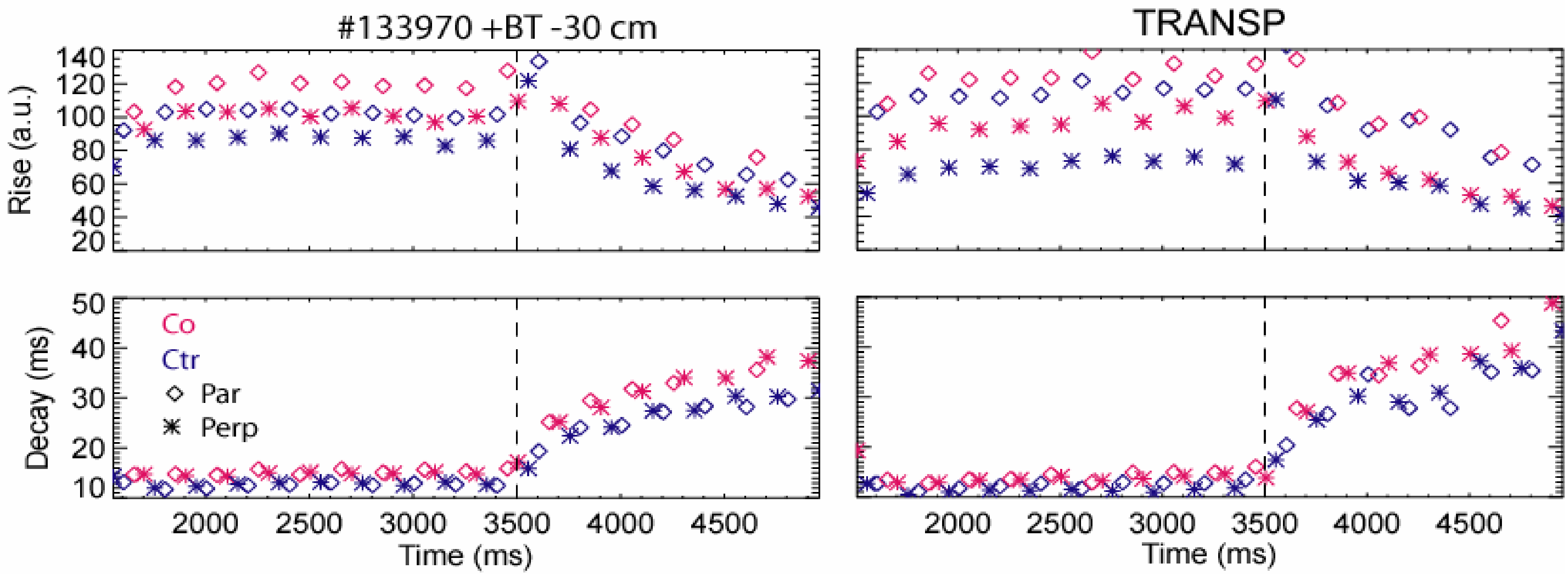
Beam-Blip Technique Measures Prompt & Delayed Losses



Nucl. Fusion 43 (2003) 883.

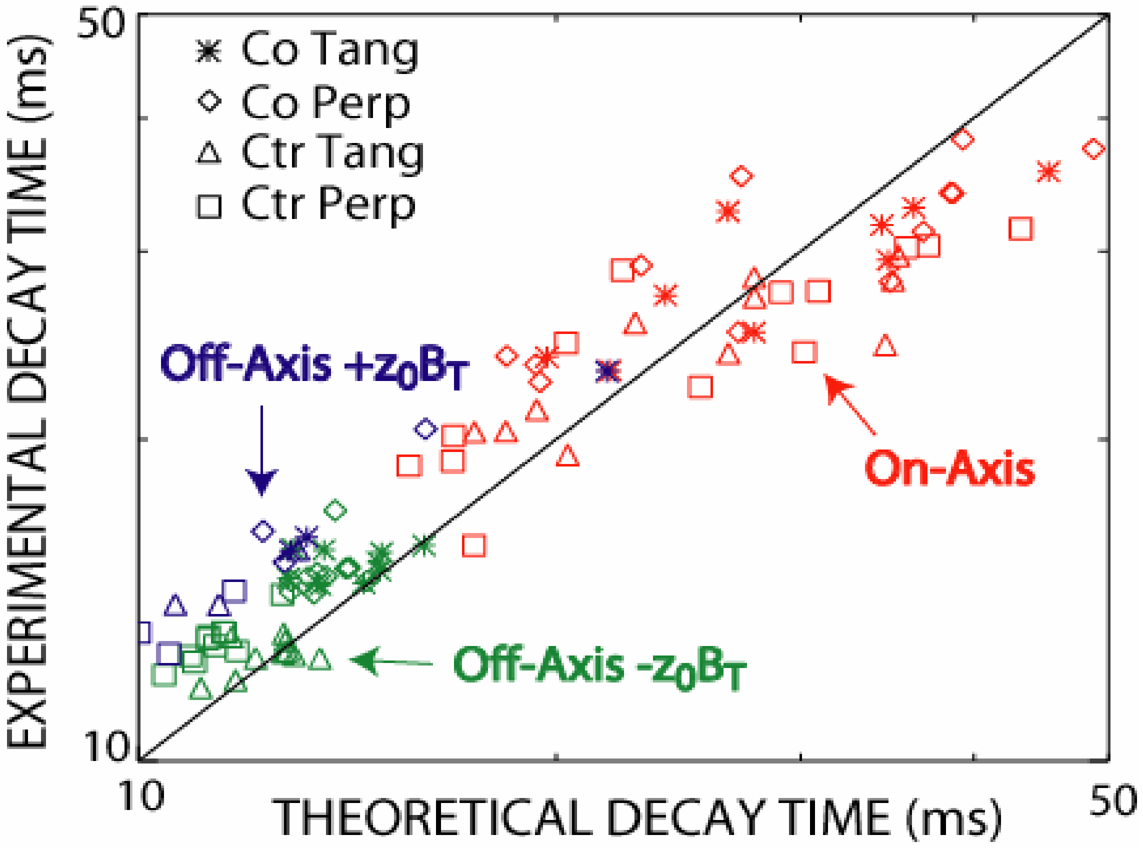
- Rise depends on number of confined beam ions injected
- Decay depends on slowing down & losses on τ_s timescale
- Excellent fits to model equations for all of these data

Beam Blip Data Compared with Theory for a Representative Discharge



- **Co** better confined than **Counter** (less CX & orbit losses)
- **Tangential (diamond) better than Perp (*) (less shinethrough)**
- **Expected variation with density evolution (falling late here)**
- **Good agreement with TRANSP in this case**
- **On-axis better than off-axis**

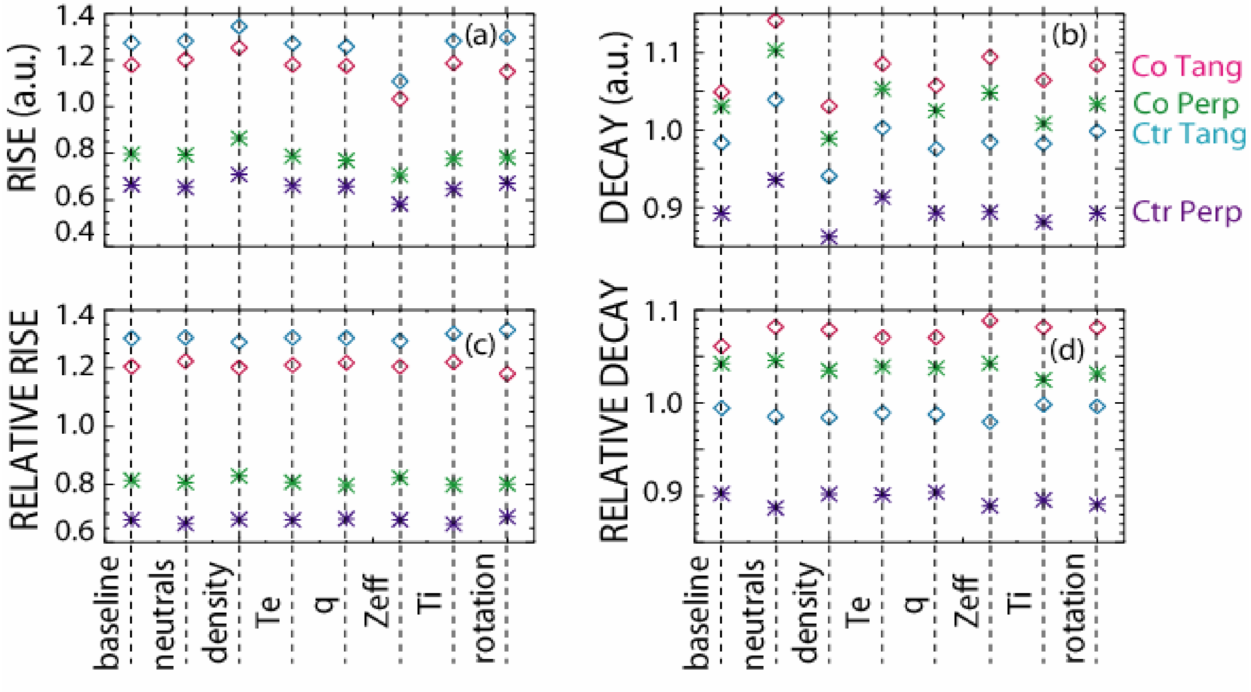
Blip Data Consistent with Expected Confinement



- Both off-axis & on-axis decay times are consistent with theory

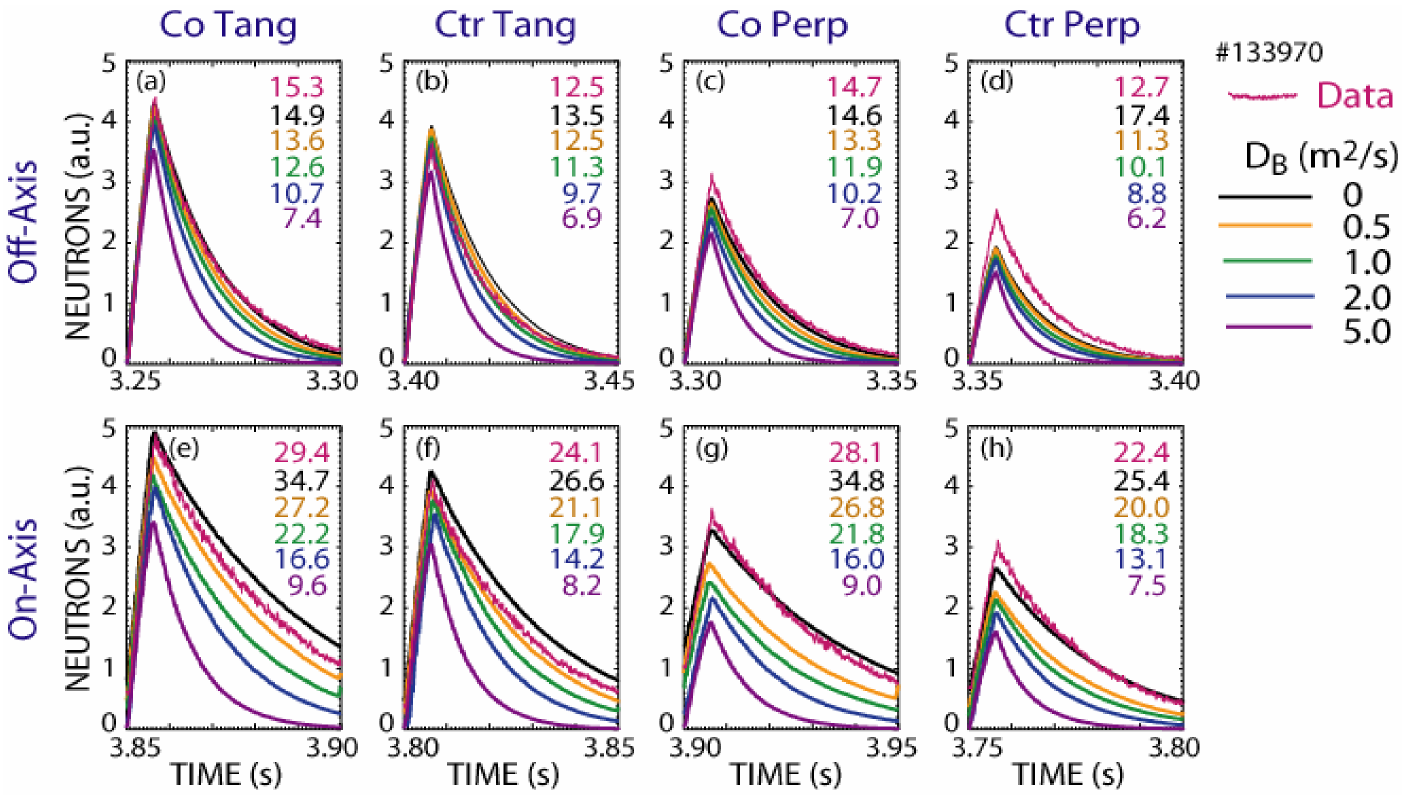
- Overall, experiment: theory = 0.98 (correlation coefficient r=0.93)

Relative Rise & Decay Predictions insensitive to experimental uncertainties



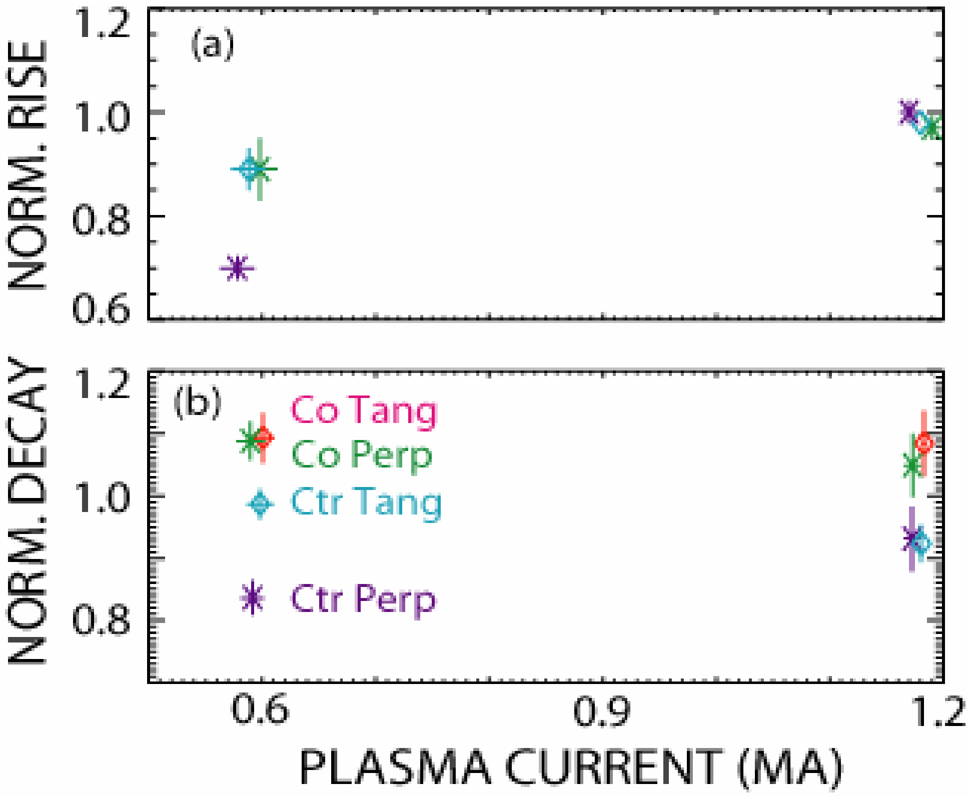
- ~20% uncertainty in absolute rise
- ~10% uncertainty in absolute decay
- Only <5% uncertainty when comparing sources

Beam blip data imply fast-ion diffusion <0.5 m²/s



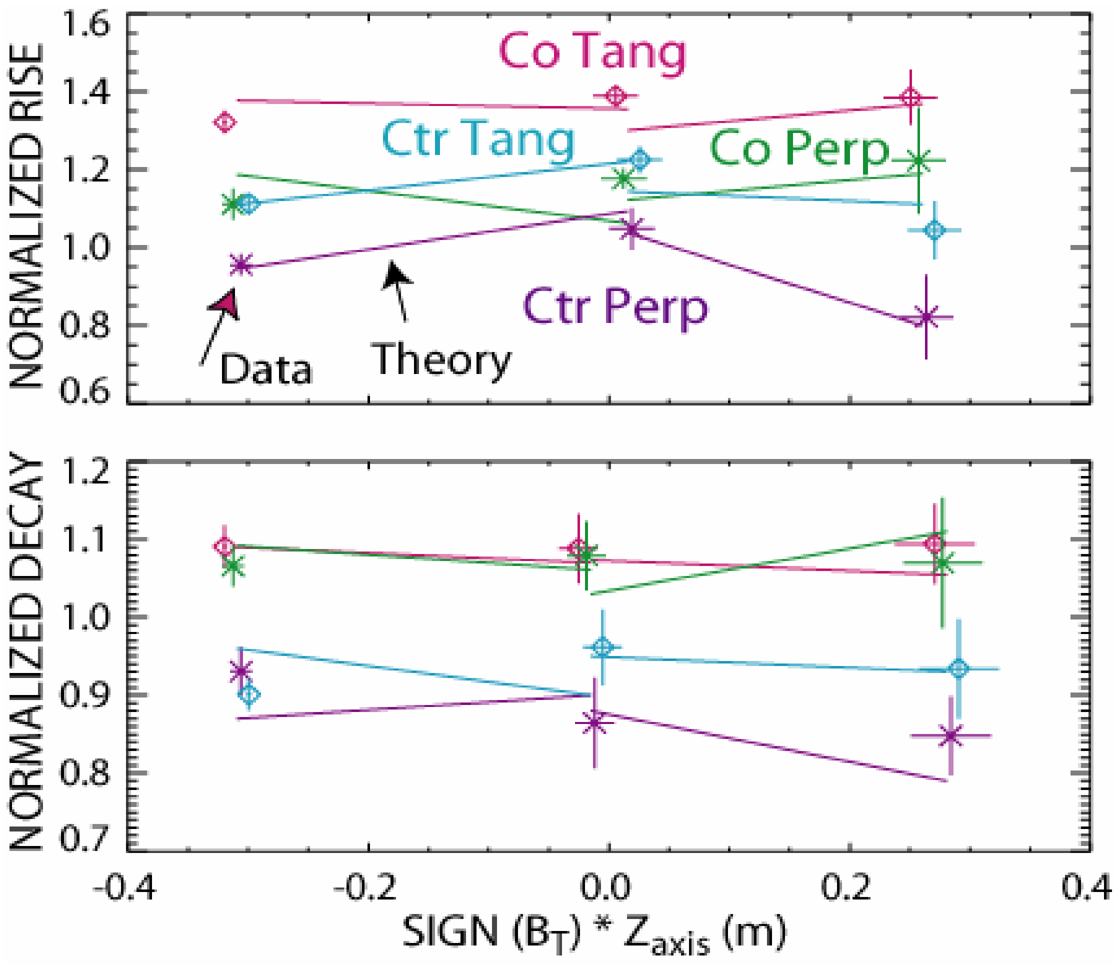
- **Numbers are from fits to curves in ms.**
- **Chi-squared is smallest for D_B=0**

Differences in confinement are greater at lower plasma current



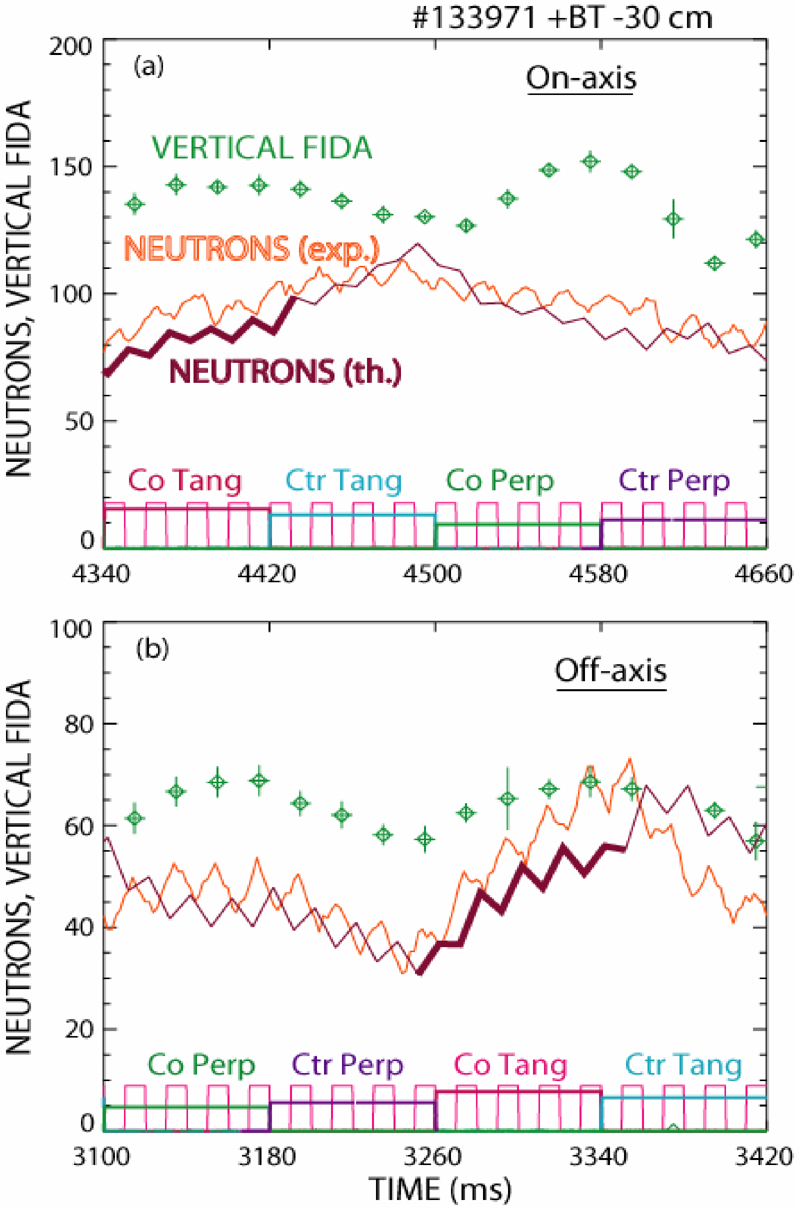
- Data from on-axis full-size plasmas
- Rise data normalized to co-tangential; Decay to average of all four beam types
- Counter Perp beam poorly confined at 0.6 MA
- Drift orbit width inversely proportional to plasma current → Differences shrink with I_p

Changing the helicity of the magnetic field has a modest effect on overall confinement



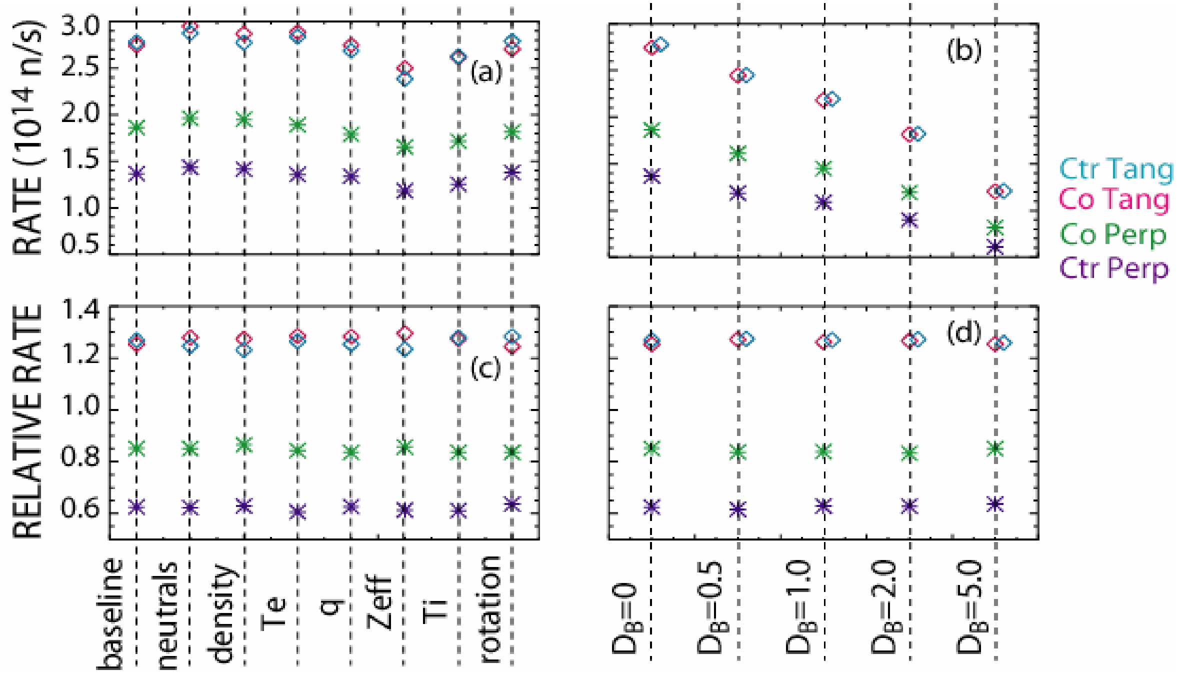
- Data from database of 302 blips
- Theory from off-axis → on-axis change in two simulated discharges
- Positive abscissa → larger pitch (for co-deposition) but farther from axis

Use cyclic injection of four sources to study confinement at modest power



- 80 ms injection pulse is comparable to slowing-down time
- Neutrons sensitive to high energy, favor counter
- FIDA favors co
- Neutron theory most reliable when 30L injects
- Relative neutron rate sometimes agrees with theory; sometimes disagrees

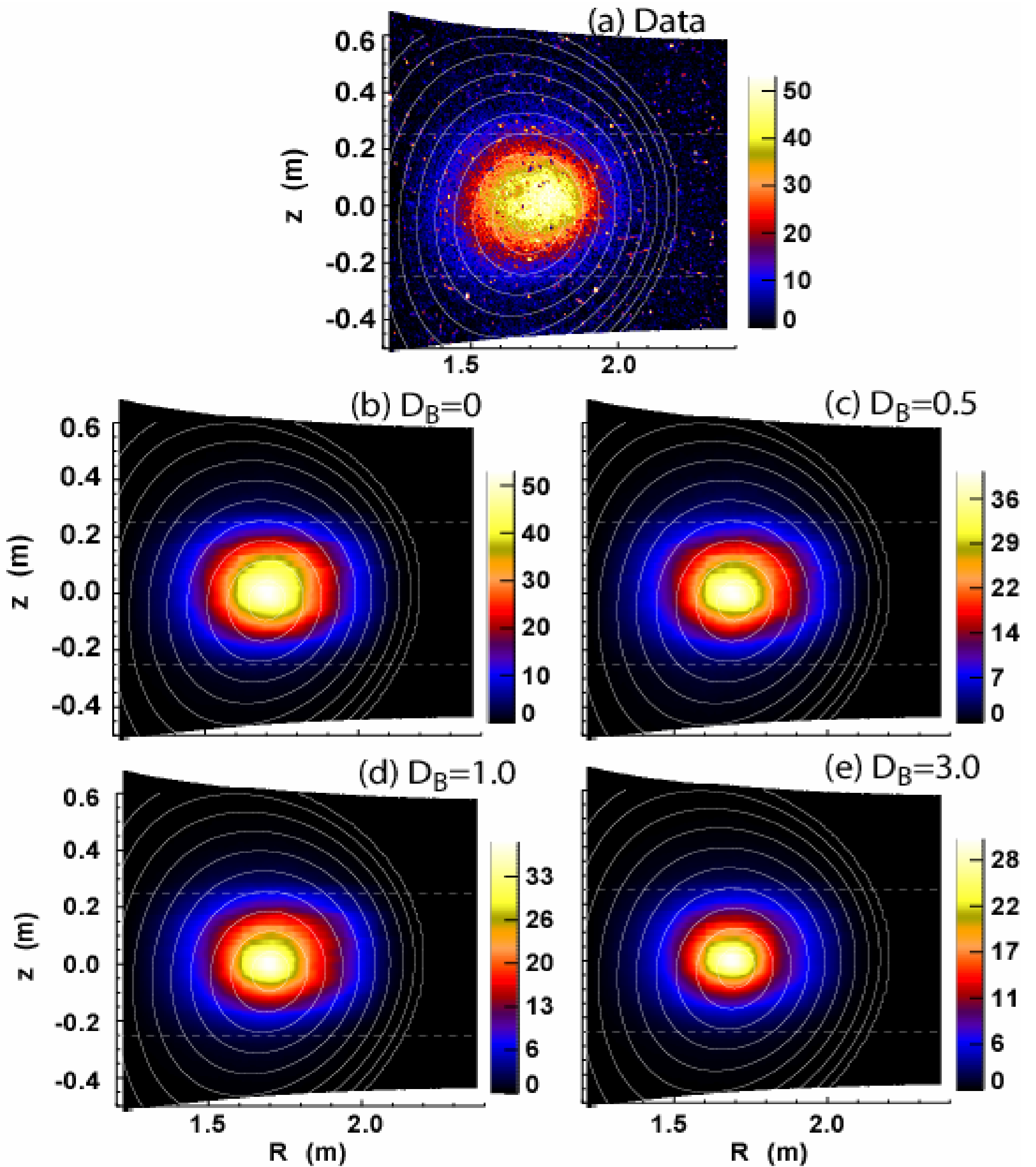
Relative neutron predictions insensitive to experimental uncertainties



- Absolute rate sensitive to uncertainties
- Weak sensitivity of relative rate.
- Relative rate insensitive to spatially uniform D_B
- Experimental differences in rate often exceed estimated uncertainties

2D FIDA image in qualitative agreement with predicted image

- For spatially-uniform D_B, shape insensitive to magnitude of diffusion
- On-axis case here



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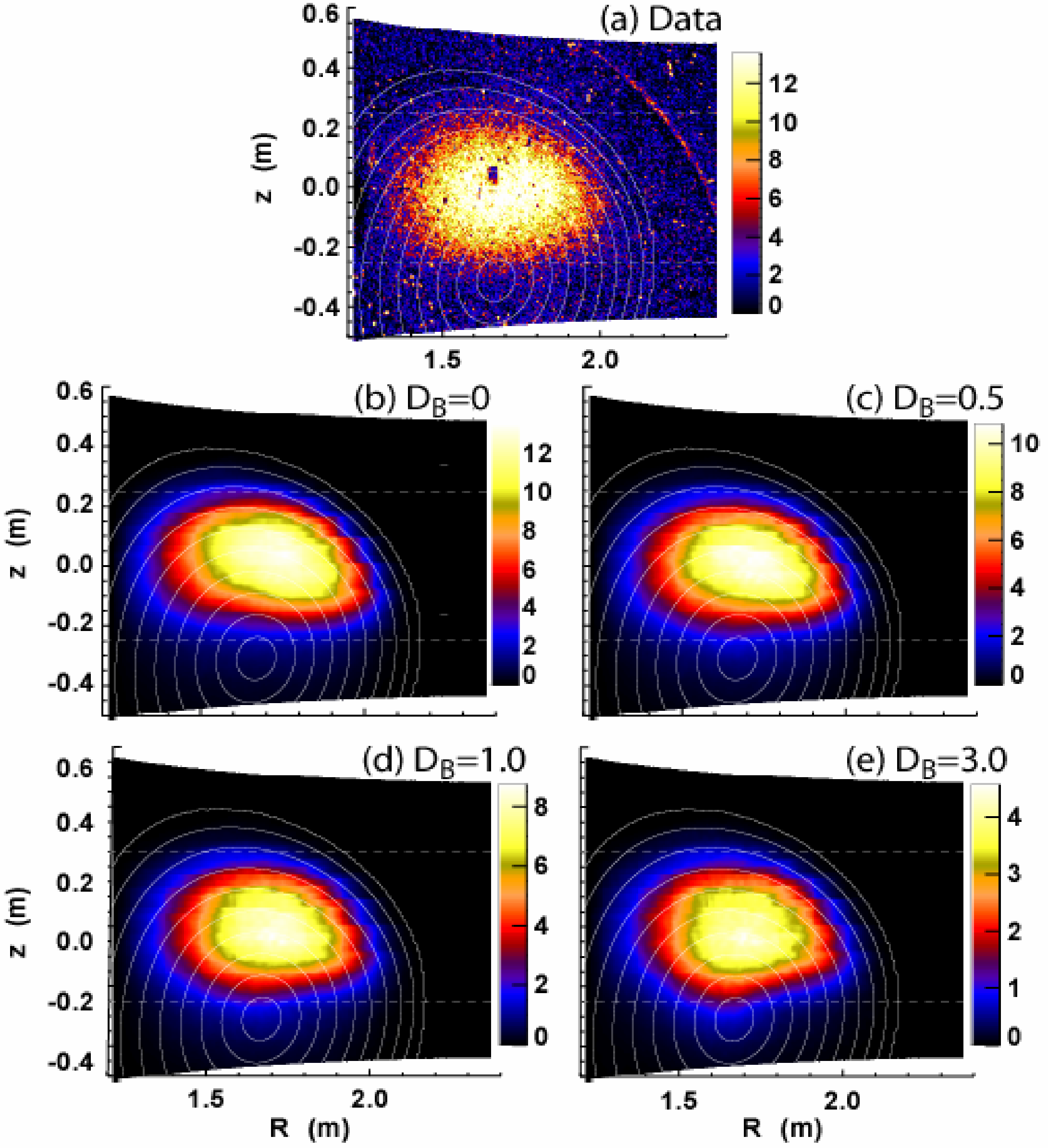

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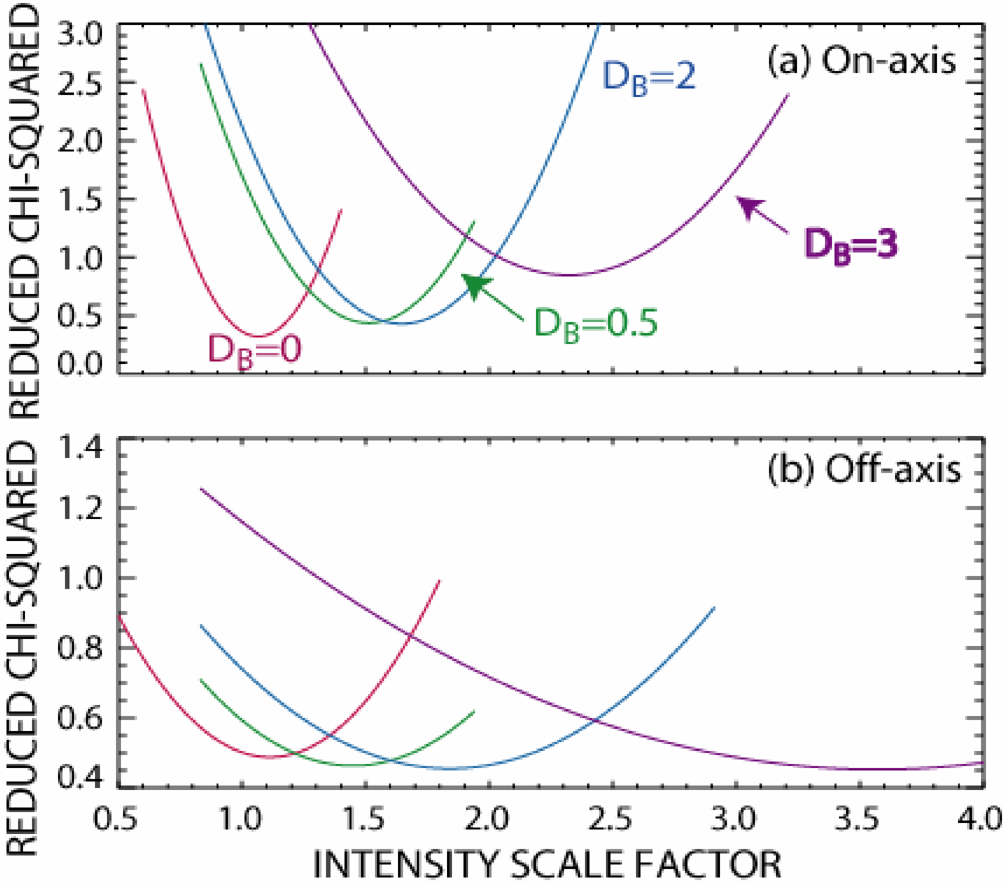
Quantitative analysis → similar diffusion in on-axis & off-axis phase



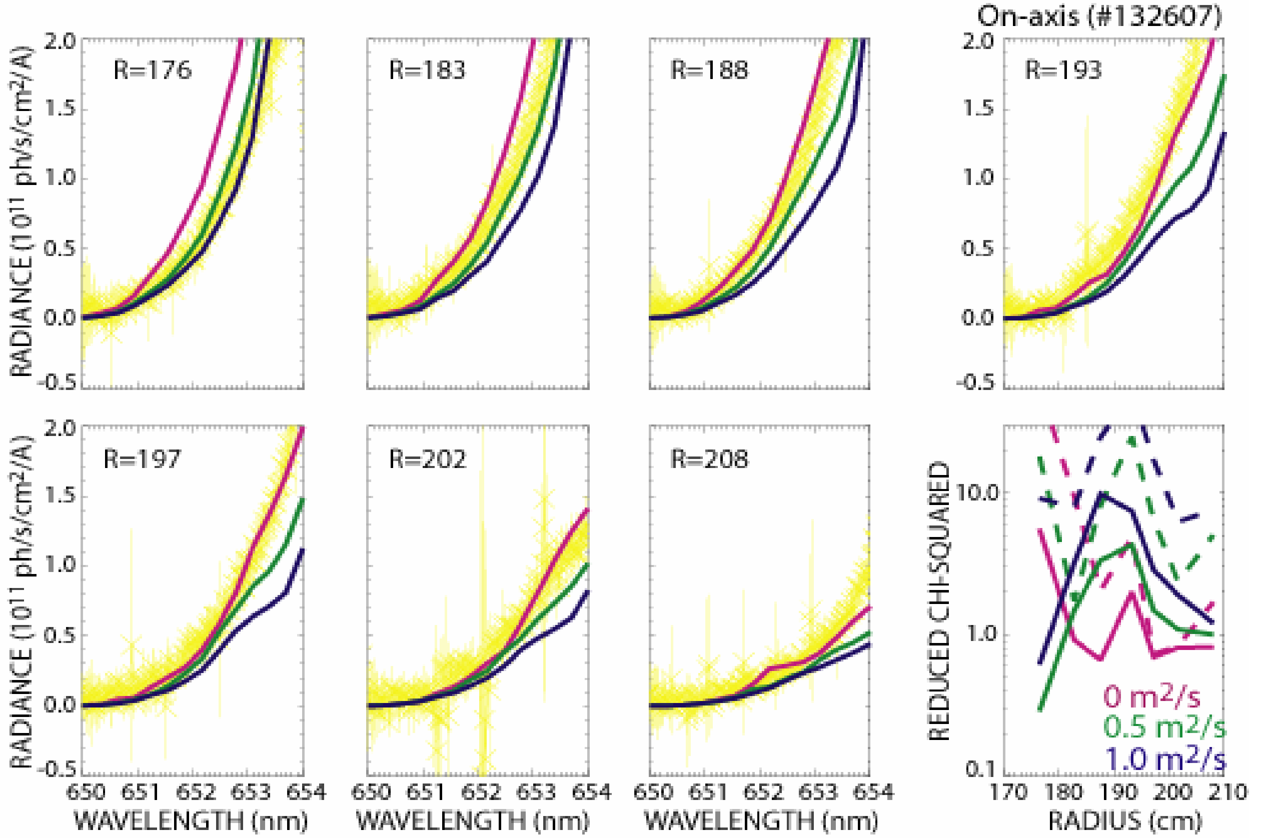
- **For 2008 data, absolute calibration is uncertain**
- **Multiply data by normalization factor**
- **Must be same factor for both cases!**
- **On-axis case agrees best with D_B=0 but other values OK**
- **Off-axis case insensitive to D_B**

FIDA spectra shape often agrees with theory

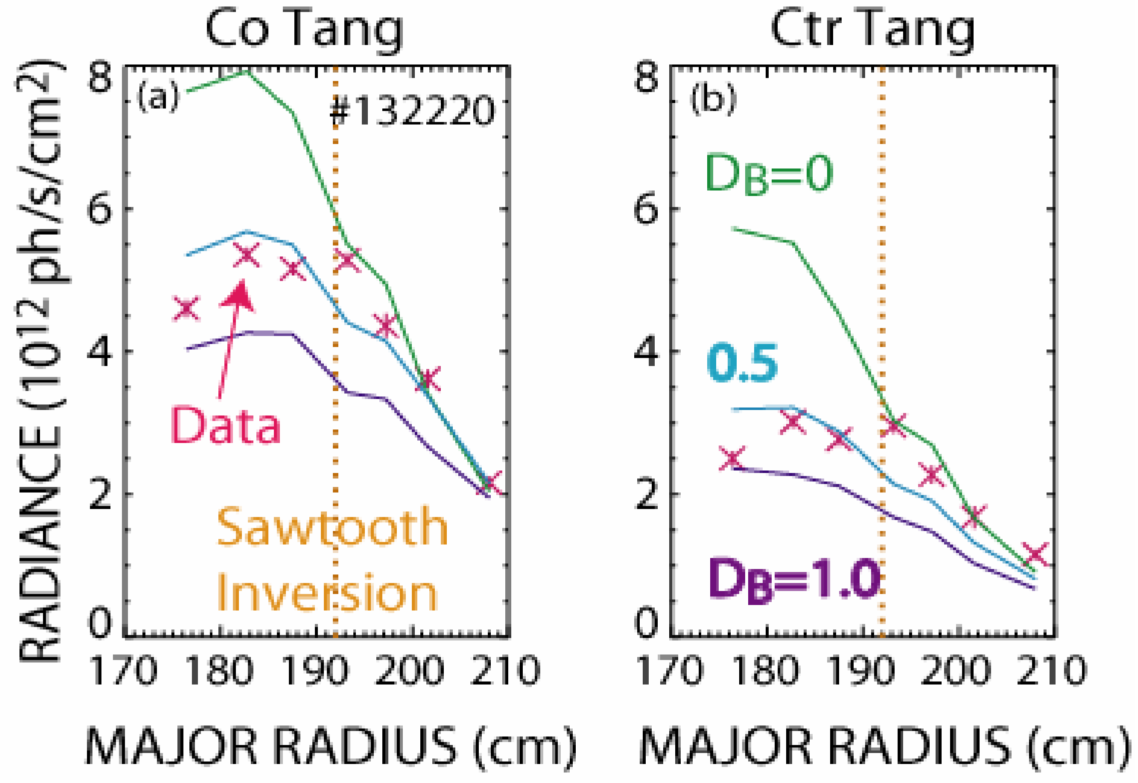
- Vertical FIDA is absolutely calibrated--no free parameters in this comparison

- Except in center, agreement is best with D_B=0

- Sawtooth may suppress central channel

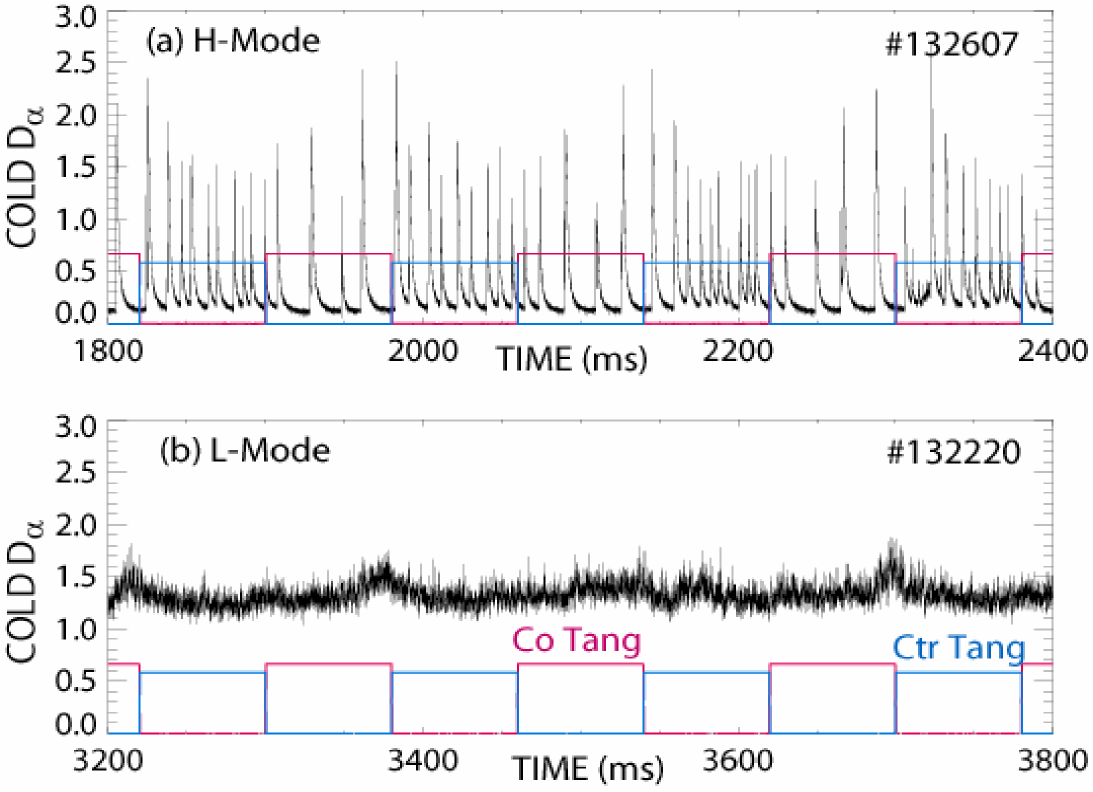


(Outside inversion radius) Agreement is good in full-size, on-axis case



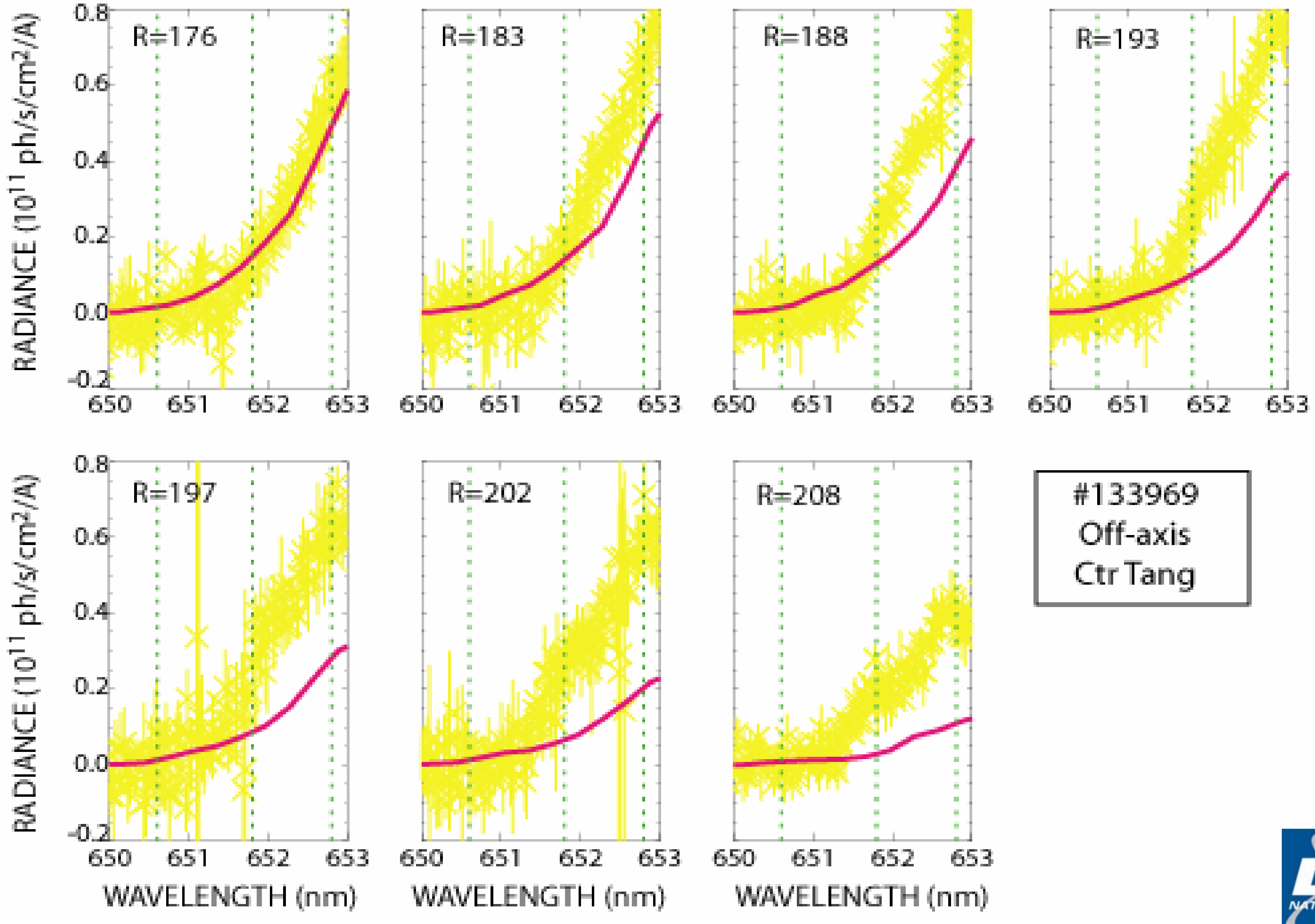
- **Radial profile agrees with no beam-ion diffusion for R > 190 cm**
- **Relative change for co/ctr switch consistent with theory**
- **Spectral shape in excellent agreement too**

ELM dependence on beam angle may introduce systematic errors in beam-angle comparison



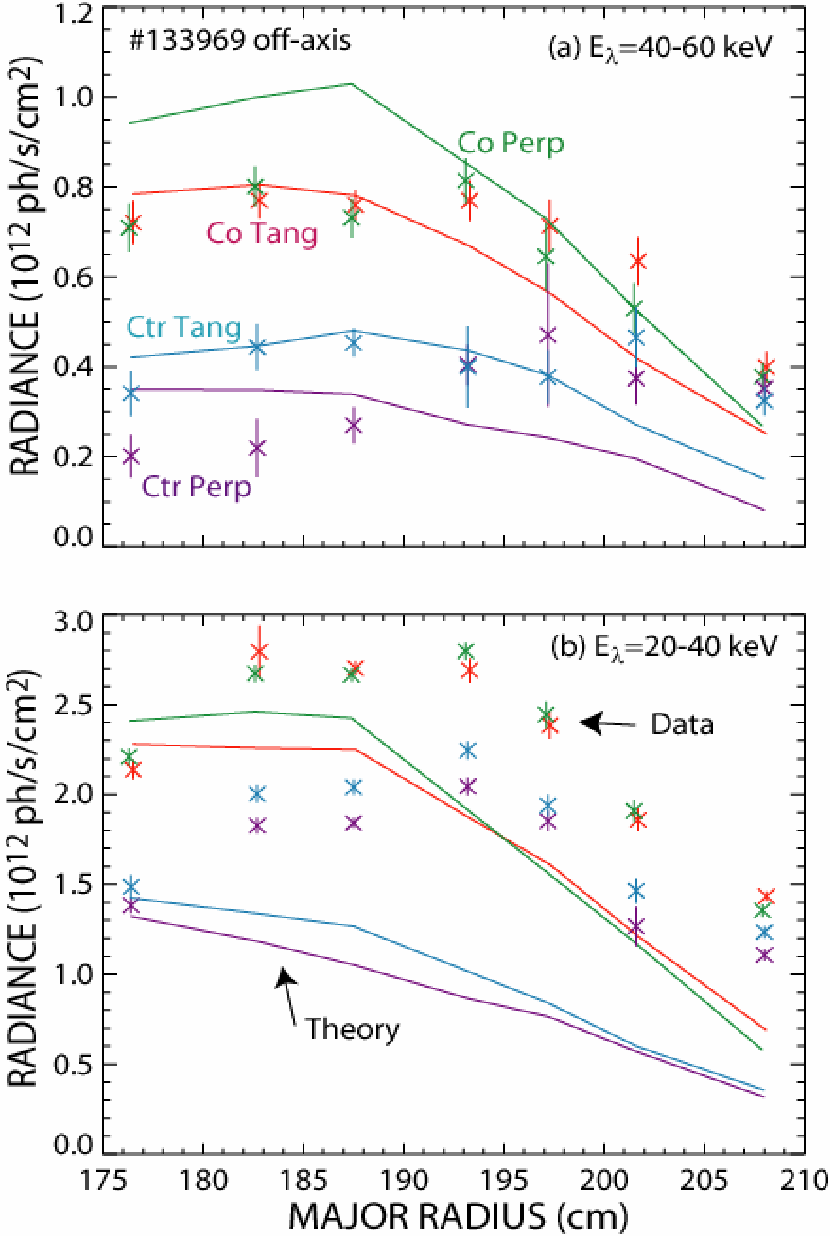
- **Some shots have reproducible correlation of ELM frequency with beam angle**
- **Edge impurity or scattered light may be different for different beams**
- **L-mode data best**
- **No obvious errors detected in H-mode discharges, however**

The FIDA spectra often deviate markedly from classical predictions



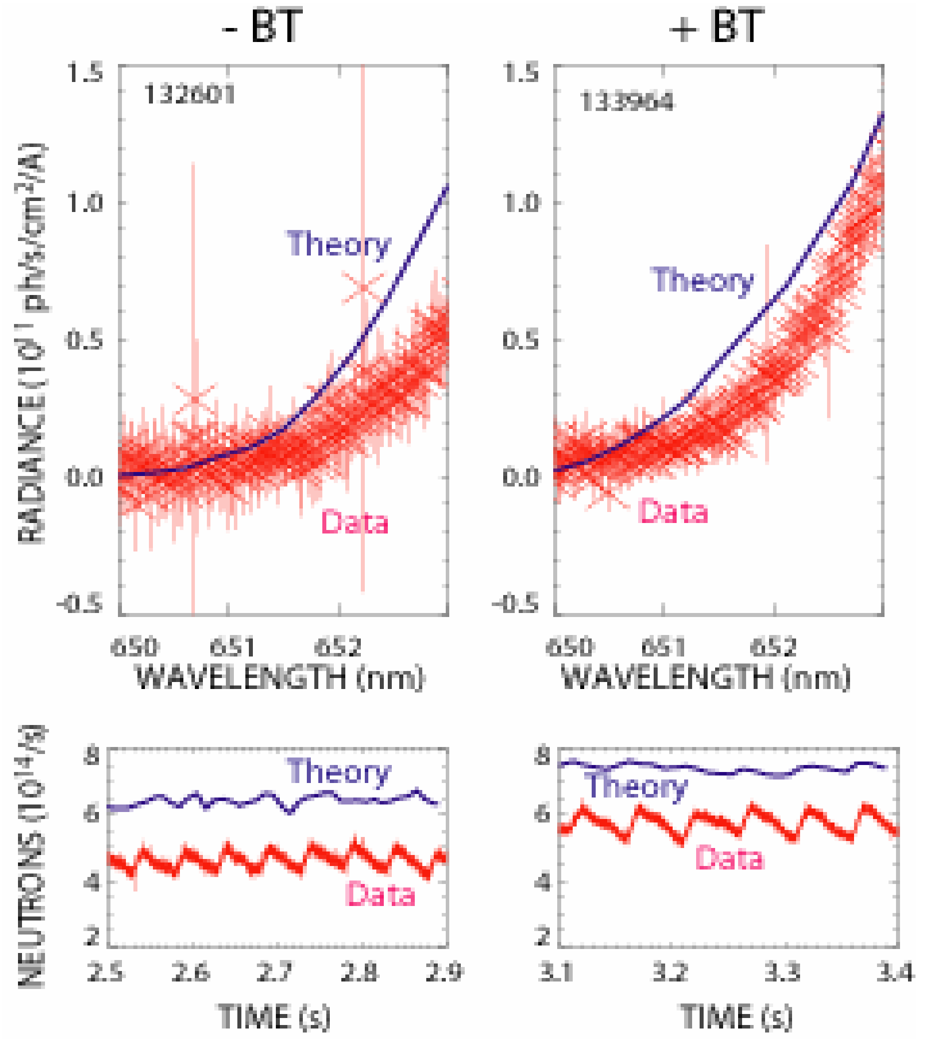
#133969
Off-axis
Ctr Tang

The FIDA profiles often deviate markedly from classical predictions



- High quality data in this L-mode case
- General trends with beam angle consistent with classical theory but profile shape is way off
- The discrepancy is larger for small Doppler shift

Fast-ion signals depend on the pitch of the magnetic field



- **Compare nearly identical down-shifted plasmas with toroidal field flipped**
- **Both vertical FIDA & neutron signals are larger with +B_T , as predicted**
- **Deviations in spectra, spatial profile, and magnitude are observed, however.**

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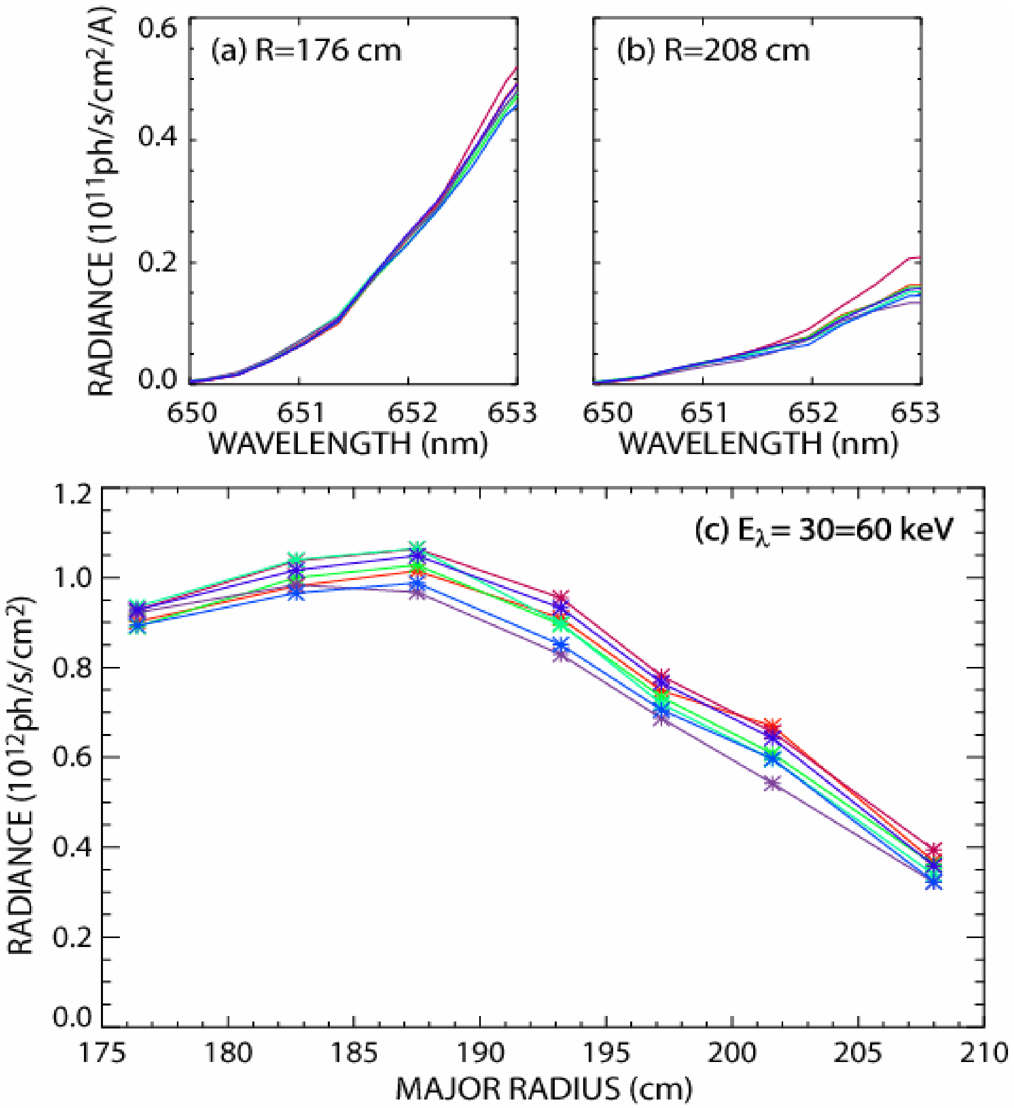
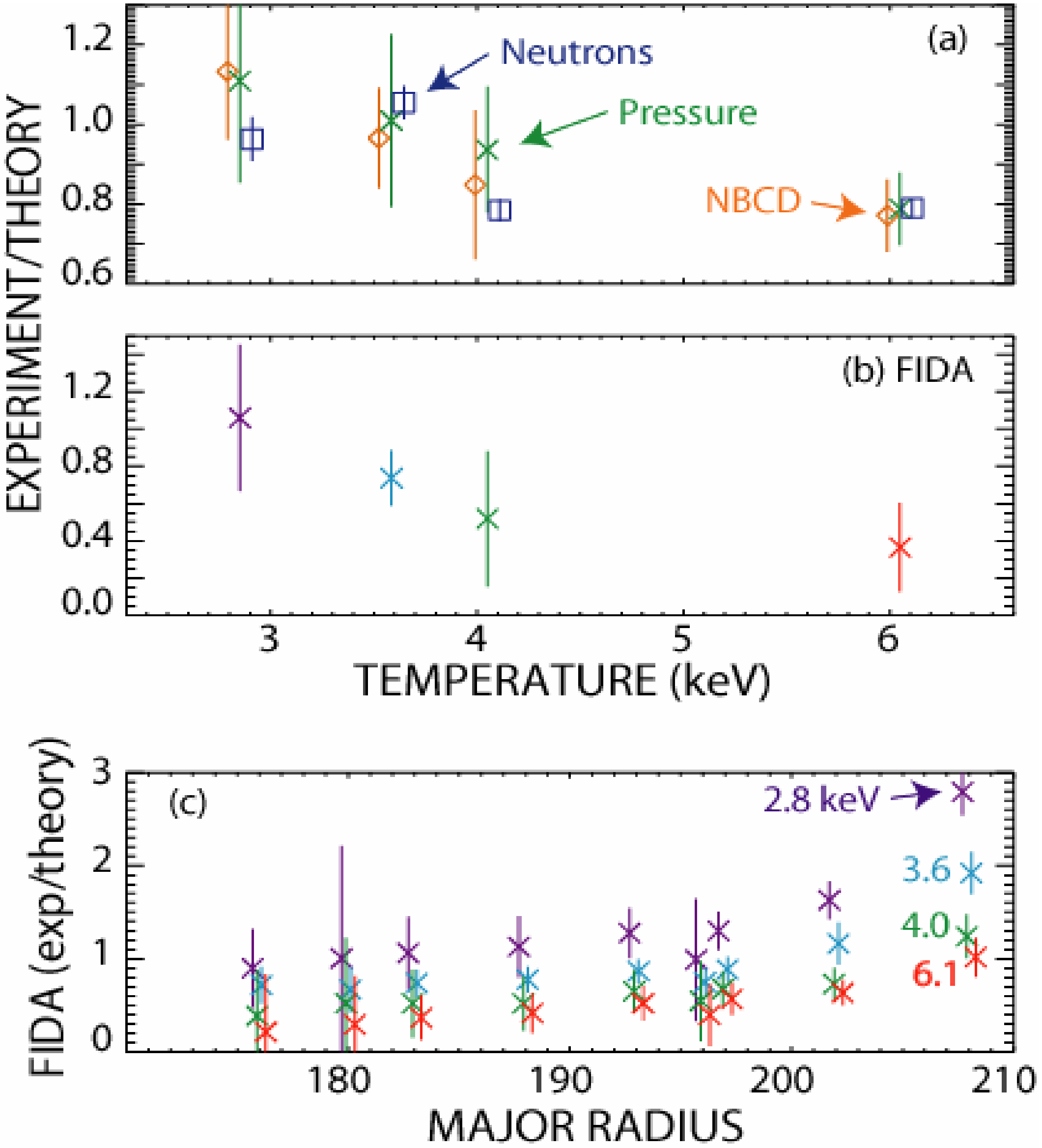
The deviations are much larger than the estimated errors due to uncertainties in the profiles



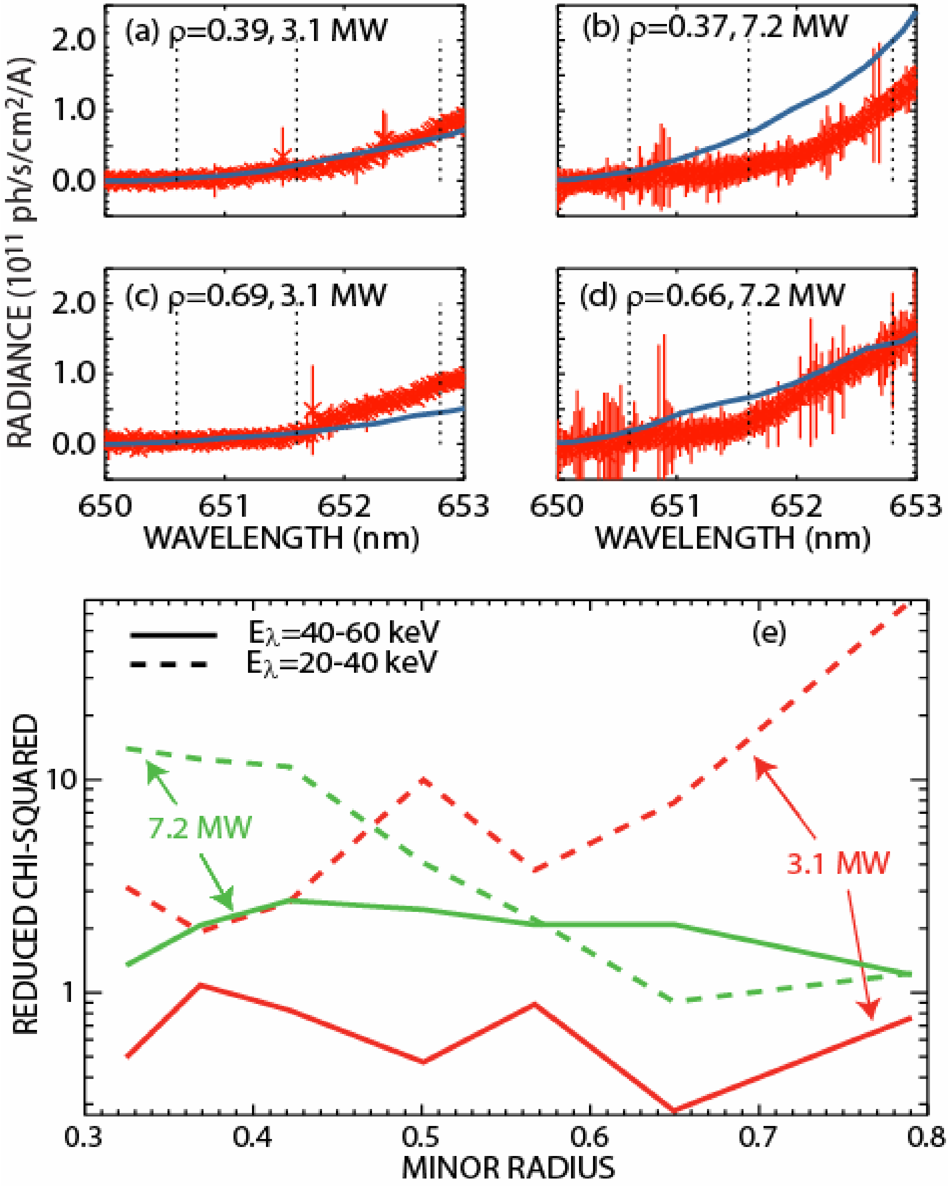
The deviations are greater in higher power shots

- 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)



The deviations are greater at lower energy

- **At low power, the central spectra agree well with theory**
- **At low power, more signal at low Doppler shift**
- **At high power, spectral shape differs at all radii and wavelengths**



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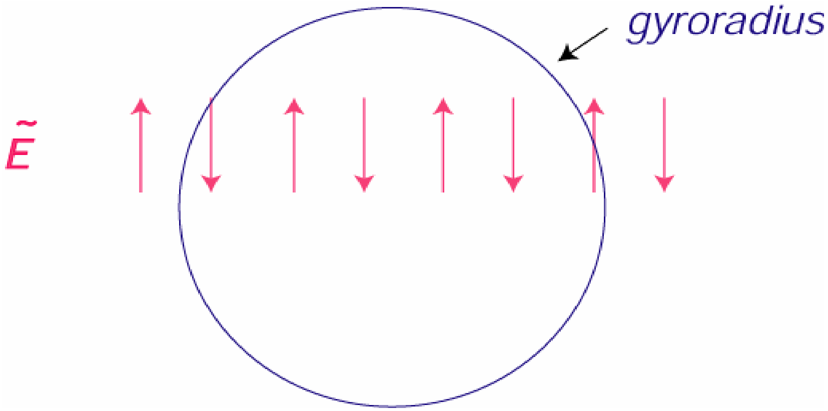
Theoretical Explanation for Small Diffusion: Large Orbits Phase Average



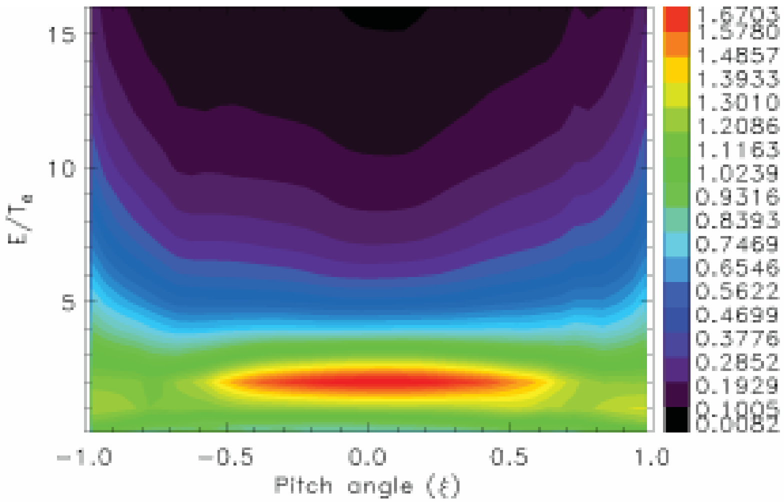


FIG. 3 (color). Diffusivity $D = D_I$ as a function of particle energy $E = T_e$ and pitch angle ξ.

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

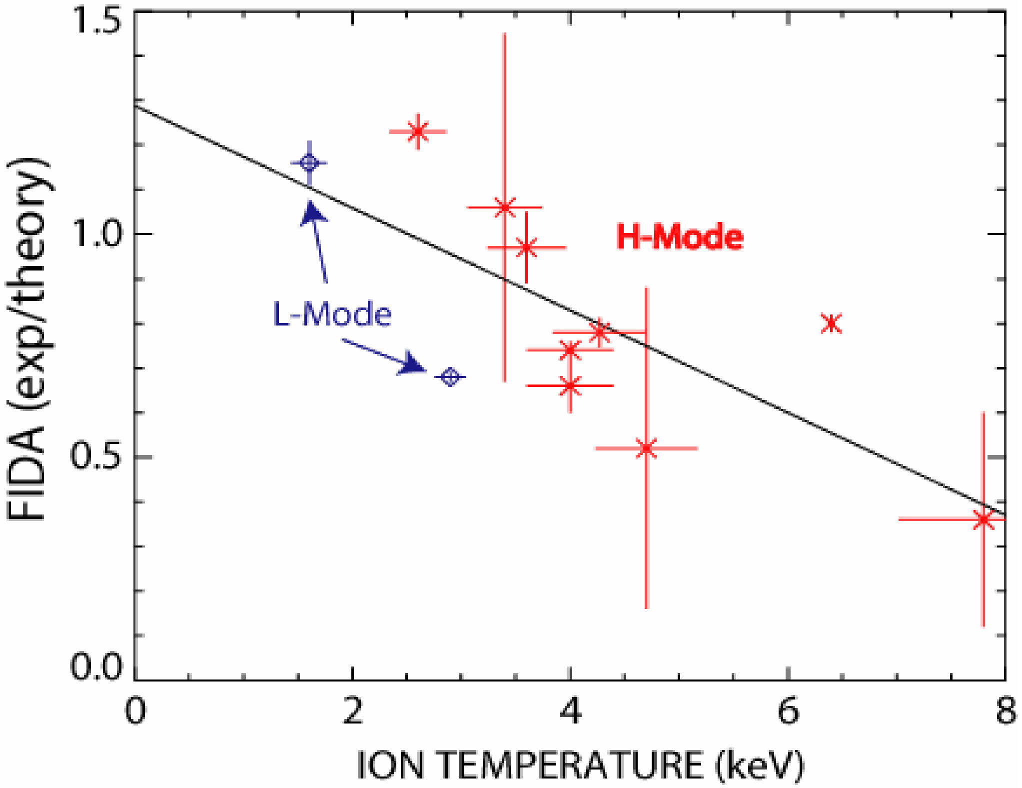
- **Analysis: Spatial & temporal averaging over turbulent fluctuations.** $J_o(k_\theta \rho_f)$

<u>Many recent publications</u>

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

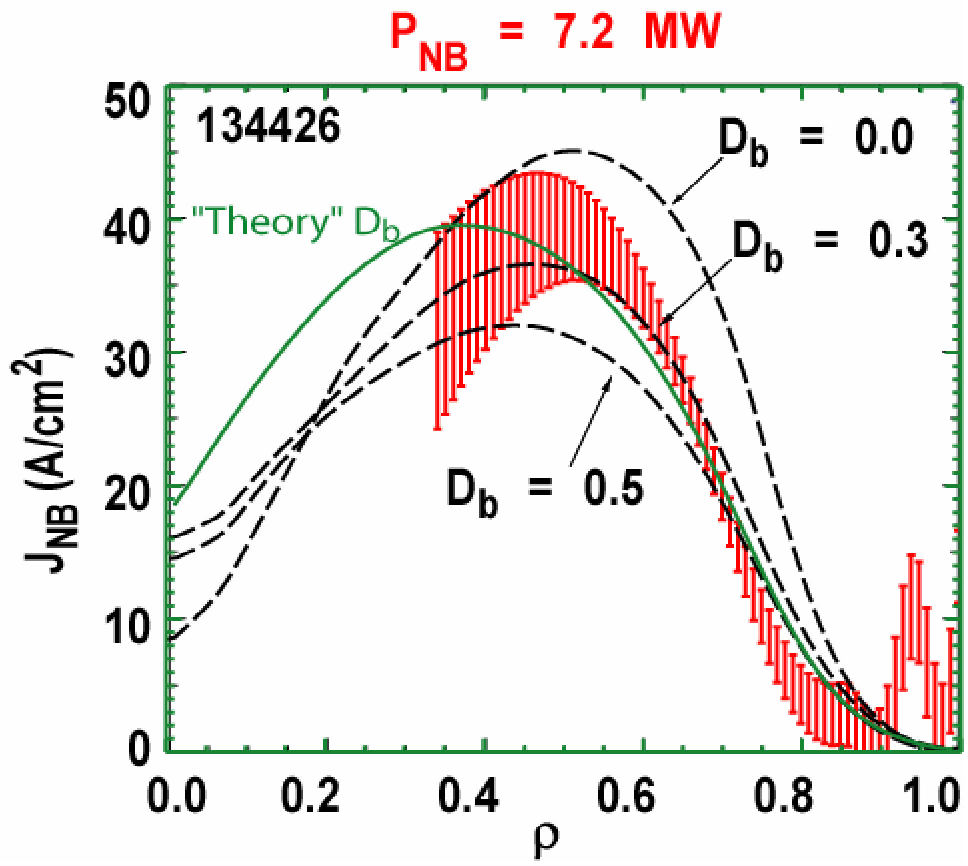
- **Transport scales with E/T (fast-ion energy/temperature)**
- **$D_B(r) = c[E/T(r)]\, D_i(r)$**

The discrepancy scales with temperature as expected for transport by microturbulence



- Similar scaling with T_e

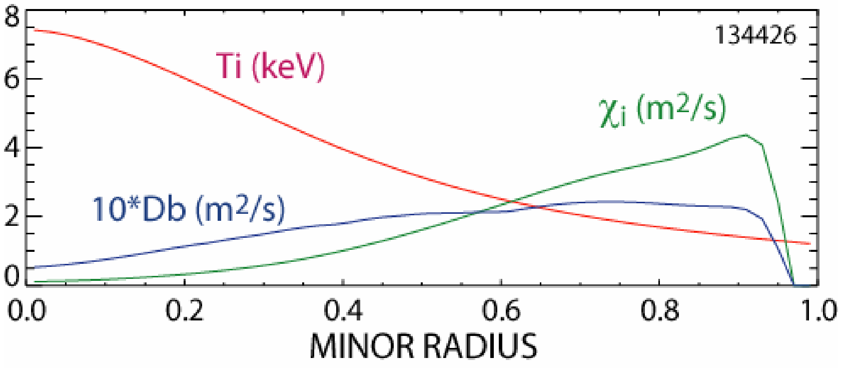
The measured NBCD shows similar discrepancies

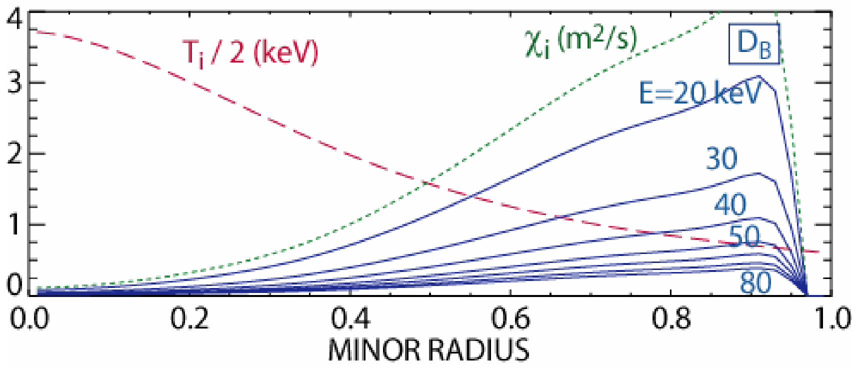


- J.M. Park empirically found that D_b~0.3 provides a decent fit to the data

- The crude theory-based D_B gives a similar profile

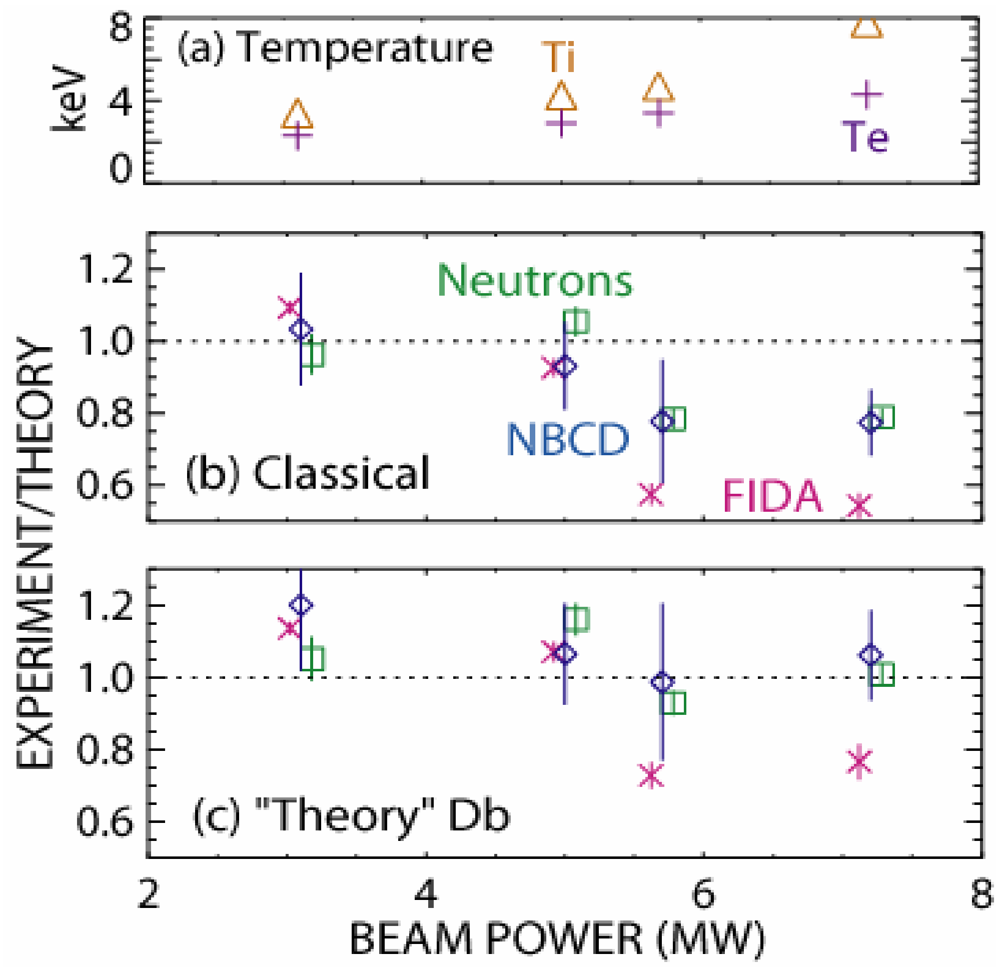
Use TRANSP D_B for quantitative estimate of expected effect





- **Want to model**
  $D_B(r)=c[E/T(r)]\ D_i(r)$
- **NUBEAM assumes separable dependence: $D_B=g(E)h(r)$**
- **First try: Use experimental value of E/T_i to estimate magnitude of transport, then multiply by χ_i**
- **Second try: Use $D_B(E)$ for a particular T_i, multiply by χ_i**
- **Both give right magnitude but neither reproduce FIDA spectra or profile**

Theory-based estimate is right magnitude

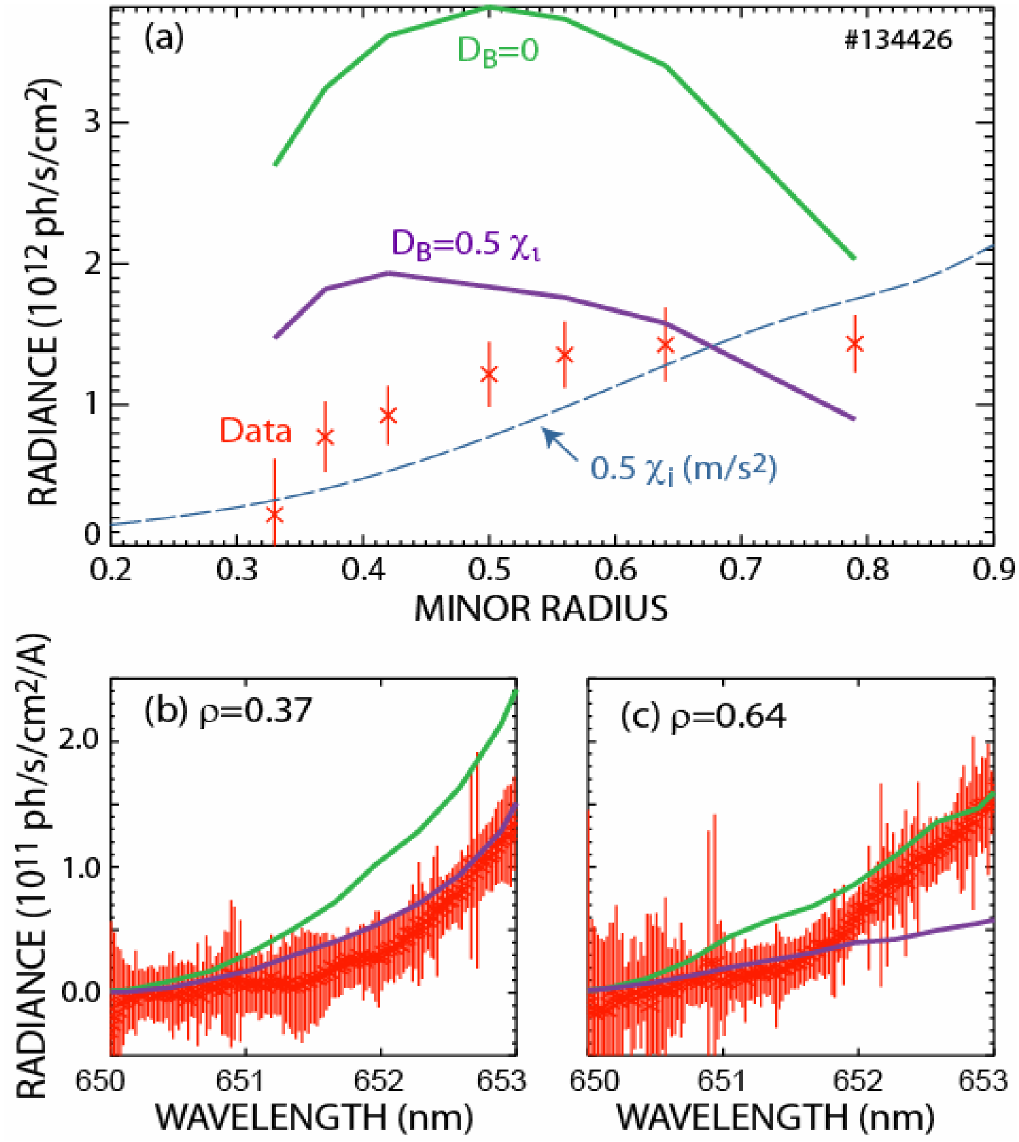


- **Neutron & NBCD data are consistent with prediction**

- **FIDA is better but still off**

- **FIDA is more sensitive to low energies than neutrons or NBCD**

The predicted transport is the right order of magnitude but the details are wrong



- This example from first modeling attempt
- The second approach yields something similar

Empirical Conclusions

- Co Tangential beams have the best confinement and counter-perpendicular the worst.
- Counter-injected beams disappear faster
- The difference between injection angles increases with increasing poloidal gyroradius.
- Off-axis trends are similar but the confinement is worse
- Fast-ion number insensitive to magnetic field helicity

Conclusions from TRANSP Simulations

- All empirical trends agree qualitatively with theory (tests orbit topology)
- The FIDA spectra shape often agrees (tests Coulomb scattering model)
- Two-D FIDA images agree with theory (tests deposition, orbits, and scattering)
- Anomalies affect all injection angles

→ NUBEAM model & parameters are OK

Conclusions about Discrepancies

- 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

Quality of Fast-ion Data is High