Energetic Ion Transport and Neutral Beam Current Drive Reduction due to Microturbulence in Tokamaks

by
D.C. Pace[1], M.E. Austin[2], E.M. Bass[3], R. Budny[4], W.W. Heidbrink[5], J.C. Hillesheim[6], C.T. Holcomb[7], M. García-Muñoz[8], B. Geiger[8], M. Gorelenkova[4], B.A. Grierson[4], S. Jardin[4], D.C. McCune[4], G.R. McKee[9], C.M. Muscatello[5], J.M. Park[10], C.C. Petty[1], T.L. Rhodes[6], G.M. Staebler[1], T. Suzuki[11], M.A. Van Zeeland[1], R.E. Waltz[1], G. Wang[6], A.E. White[12], Z. Yan[9], X. Yuan[4], and Y.B. Zhu[5]

[1]General Atomics, [2]University of Texas-Austin,
[3]University of California-San Diego, [4]Princeton Plasma Physics Laboratory,
[5]University of California-Irvine, [6]University of California-Los Angeles,
[7]Lawrence Livermore National Laboratory,
[8]Max-Planck Institut für Plasma Physik, [9]University of Wisconsin-Madison,
[10]Oak Ridge National Laboratory, [11]Japan Atomic Energy Agency,
[12]Massachusetts Institute of Technology

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

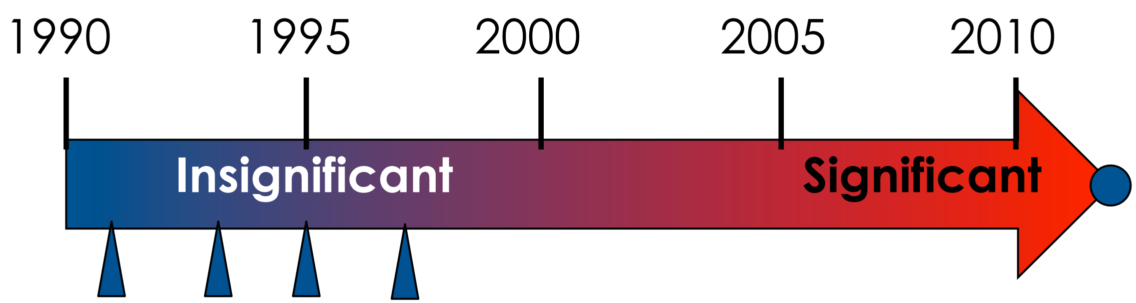
IPP Max-Planck-Institut für Plasmaphysik

ASDEX Upgrade

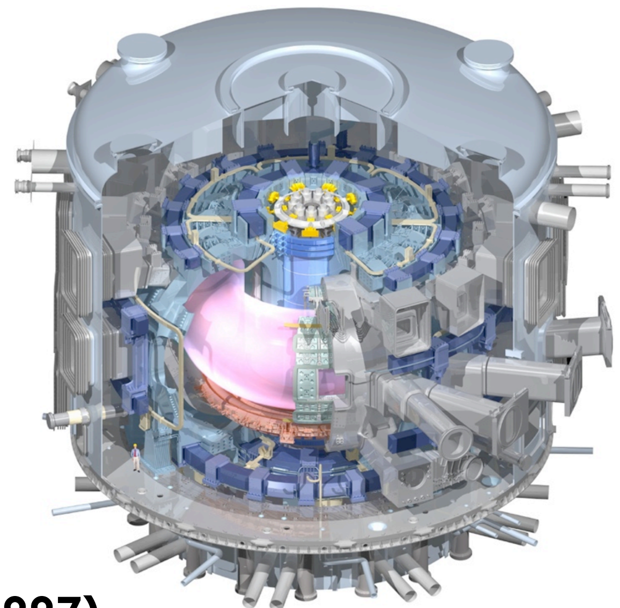
GENERAL ATOMICS

Concern for Turbulent Transport of Energetic Ions in ITER has Fluctuated Over Time

Energetic Ion Transport by Microturbulence



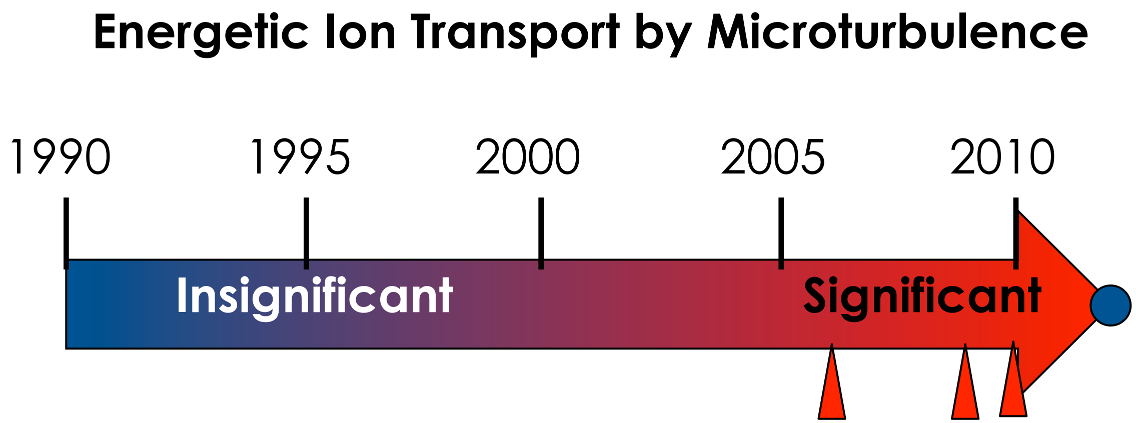
ITER

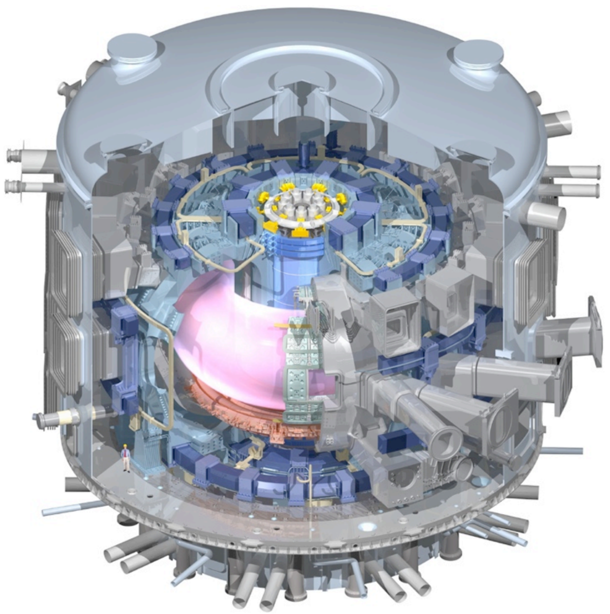


- **TFTR: beam ion and fusion product transport is classical through slowing-down, except for MHD and ripple effects (Zweben, NF 1991; Ruskov, NF 1995; McKee, NF 1997)**

- **DIII-D: record β_Φ = 11% shot demonstrated fusion product confinement most sensitive to MHD (Duong, NF 1993)**

Concern for Turbulent Transport of Energetic Ions in ITER has Fluctuated Over Time



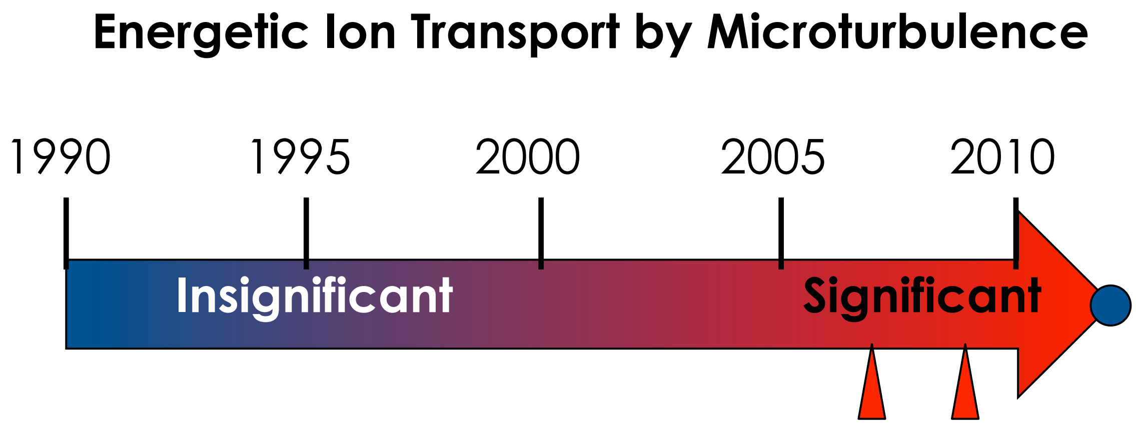


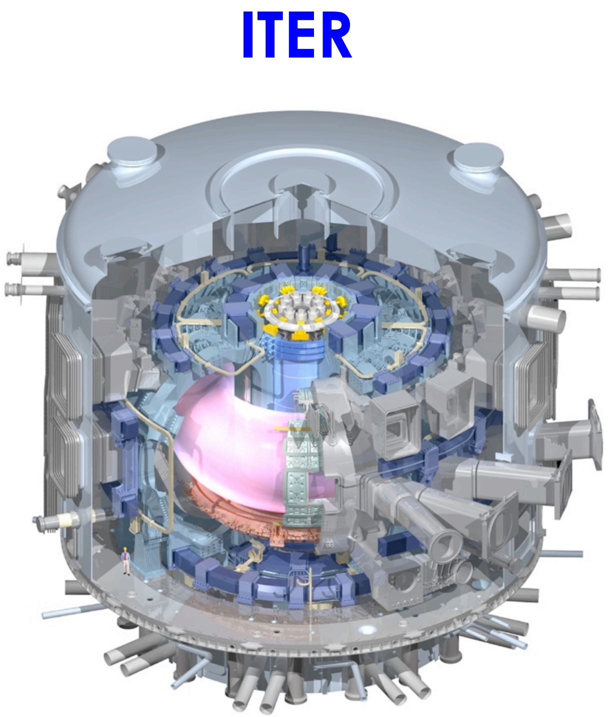
Theory: fusion α-particles and beam ions experience enhanced diffusion due to microturbulence in present day and ITER regimes (Estrada-Mila, POP 2006; Hauff, PRL 2009; Albergante, NF 2010)

Energetic ion diffusivity due to microturbulence

$$D_B \sim C \left(\frac{T}{E}\right)^{\gamma}$$

Concern for Turbulent Transport of Energetic Ions in ITER has Fluctuated Over Time





ASDEX Upgrade & DIII-D: current drive from off-axis NBI is lower than predicted, evidence for beam ion diffusion due to microturbulence (Günter, NF 2007; Heidbrink, PRL 2009)

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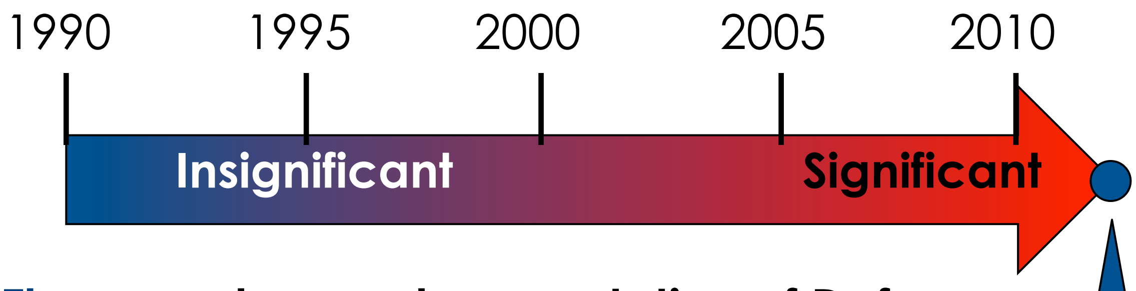
Energetic Ion Transport by Microturbulence



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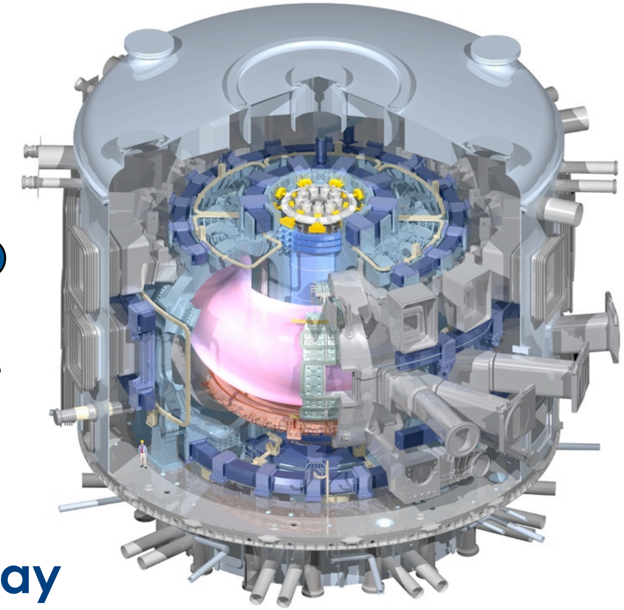


- **Theory**: advanced computation of D_B from quasilinear ratio

$$D_B = \left(\frac{D_{\mathrm{EI}}}{\chi_i}\right)_{\mathrm{theory}} \chi_{i,\mathrm{exp}}$$

← results shown today

- **Modeling**: updated projections find **no impact on ITER performance**, identify possible issues for DEMO (Albergante, Ph.D. Thesis, 2011)

- **Experiment**: DIII-D experiments and modeling indicate that energetic ion transport due to microturbulence is negligible

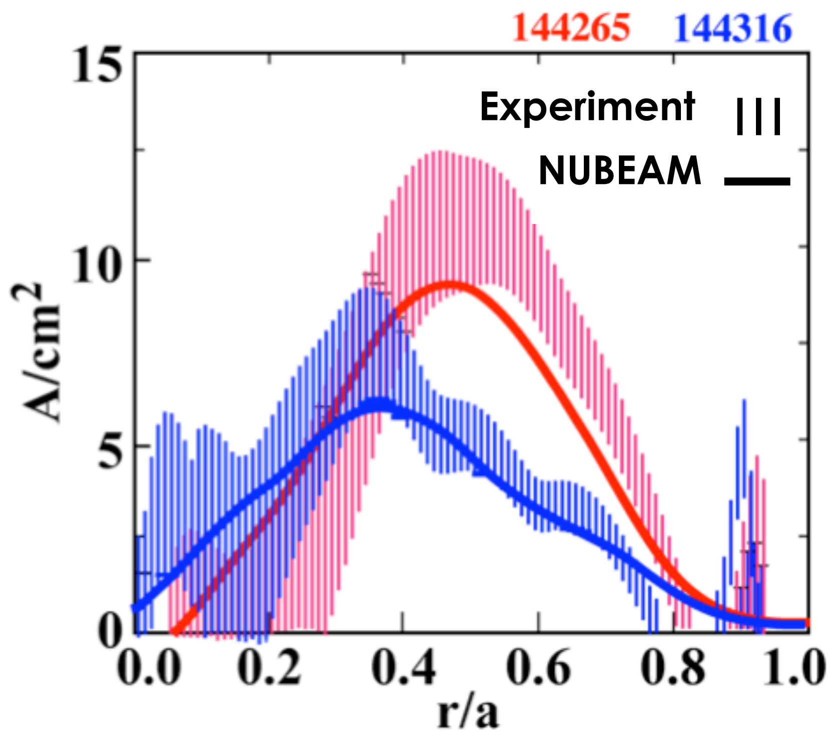
Extensive Experimental and Computational Study Finds that Microturbulence is an Insignificant Contributor to Energetic Ion Transport

- **Measured radial profiles of NBCD are well described by theory, neglecting turbulent transport, in high-performance plasmas**

- **Energetic ion transport is classical in well-documented, turbulent plasmas**

- **New modeling tools allow for predicting energetic ion diffusion due to microturbulence**
  - TGLF/DEP: calculates energetic ion turbulent diffusivity, $D_B = D_B(E, v_{||}/v, R, t)$
  - NUBEAM: applies D_B to beam ions

Neutral Beam Current Drive



J.M. Park, IAEA 2012

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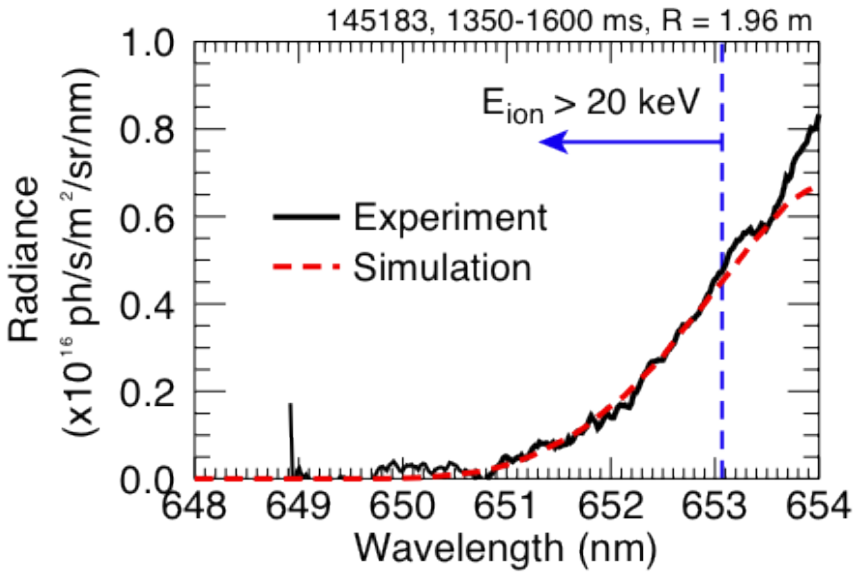
Fast Ion Spectroscopy



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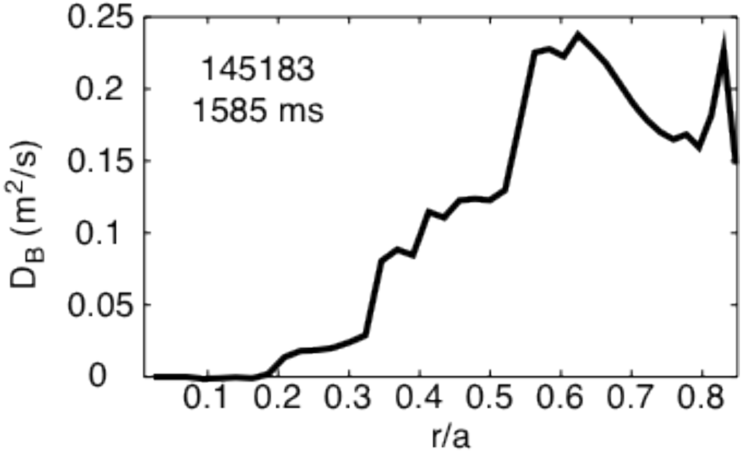
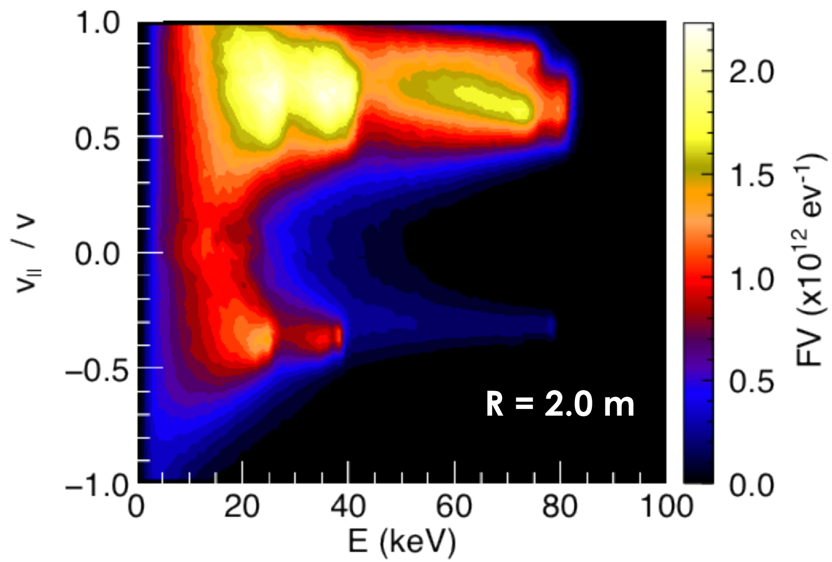
D_B from DEP



F_{beam} from NUBEAM



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Classical Energetic Ion Transport is Documented in Turbulent Plasmas During On-axis or Off-axis Beam Injection

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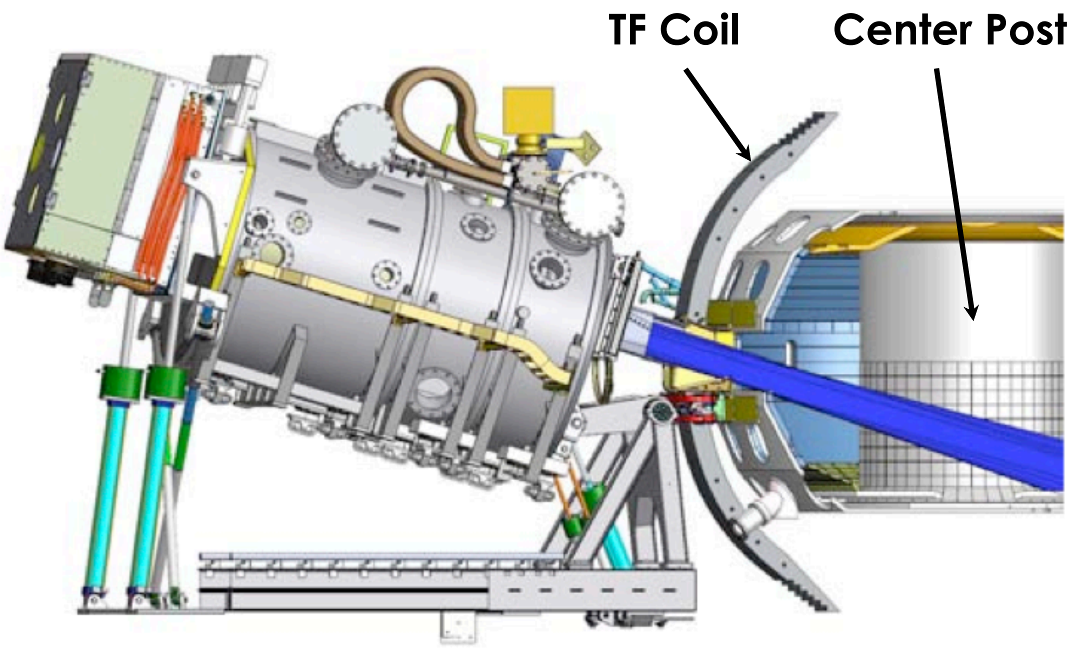
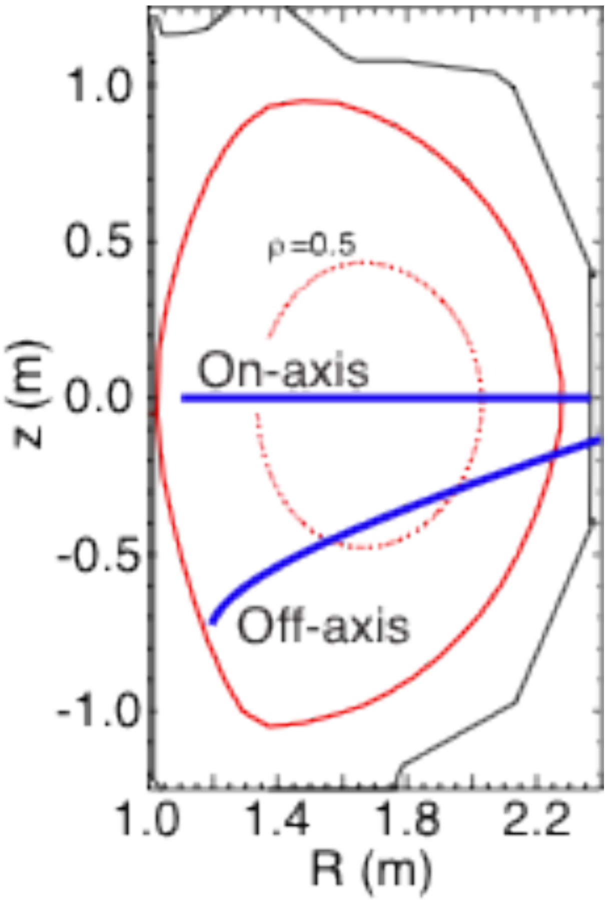
- **Experimental results and comparisons with modeling**
  - Off-axis NBCD in **DIII-D**: turbulent, L-mode plasmas
  - On-axis neutral beam injection in **DIII-D**
  - **ASDEX Upgrade**: comparisons with on- and off-axis neutral beam injection

Vertically Steerable Neutral Beam Provides 5 MW of Off-axis Injection into DIII-D Plasmas



Murphy, et al., SOFE 2011



Adapted from Heidbrink, et al., *NF* **52**, 095004 (2012)

Experimentally Determined Profiles of NBCD Require High-Quality Motional Stark Effect Measurements and Equilibria

- **Experimental beam driven current profiles, $J_{NB}(\rho)$, given by,**

$$J_{NB}(\rho) = J_{Tot} - J_{Oh} - J_{BS}$$

Determined from magnetic field pitch angle measurements (J_{Tot})

Determined from magnetic equilibria (J_{Oh})

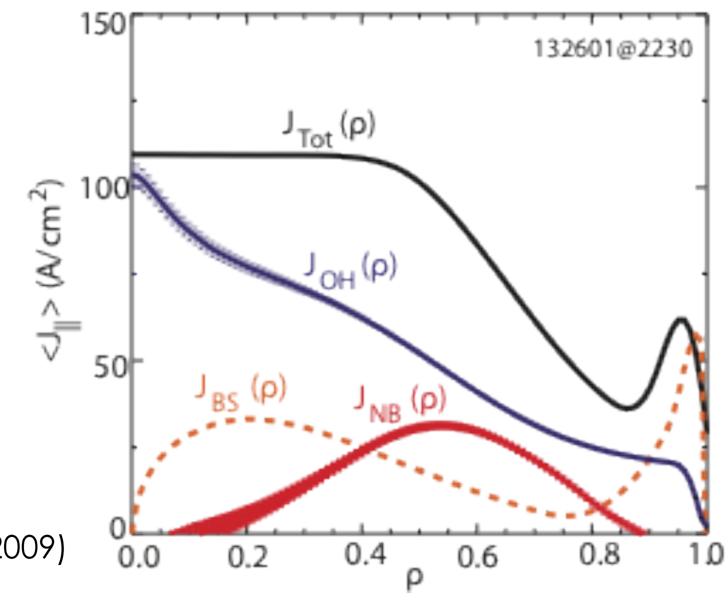
Calculated using measured profiles [Sauter, Angioni, and Lin-Liu, *POP* **6**, 2834 (1999)] (J_{BS})

- **Accurate Ohmic current profiles require excellent equilibria**

$$J_{\mathrm{Oh}}(\rho) = \sigma_{\mathrm{neo}} \frac{\partial \psi}{\partial t}$$

Ferron, VI3.00002, Thursday Afternoon

Park, NO4.00013, Wednesday Morning



Park, et al., *POP* **16**, 092508 (2009)

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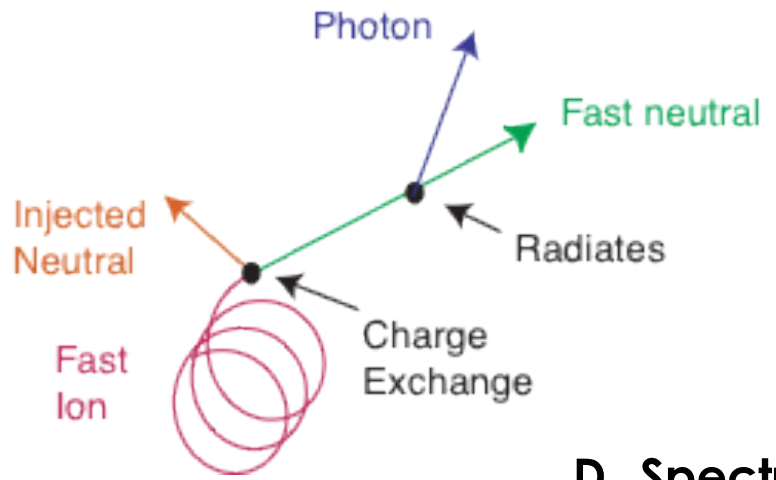
Fast Ion D_α (FIDA) Systems Measure the Energetic Ion Distribution through Charge Exchange Spectroscopy

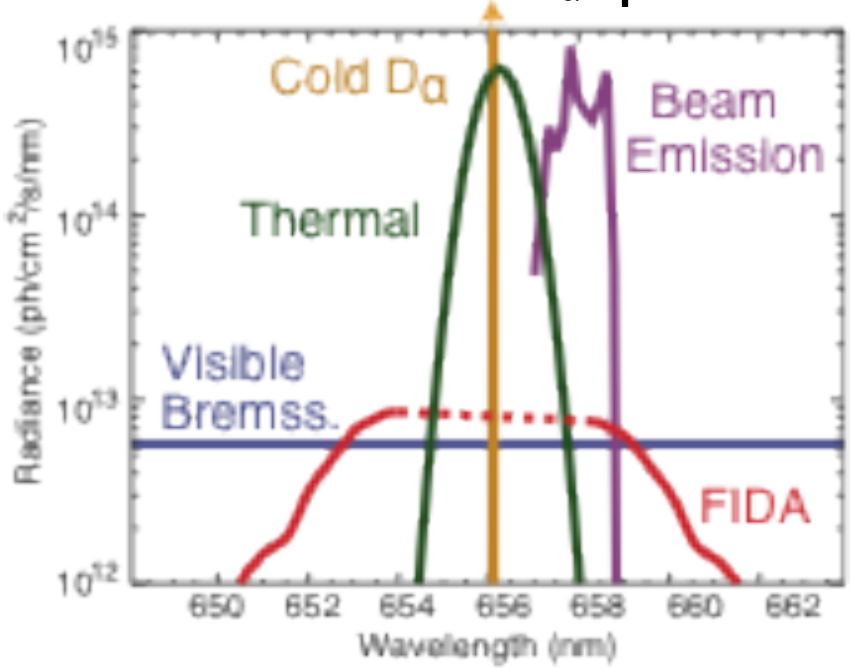
- **Injected beam neutrals charge exchange with existing fast ions**

- **Resulting fast neutrals emit Doppler shifted light based on ion velocity along a sightline**

Heidbrink, et al., *PPCF* **46**, 1855 (2004)
Heidbrink, et al., *RSI* **81**, 10D727 (2010)

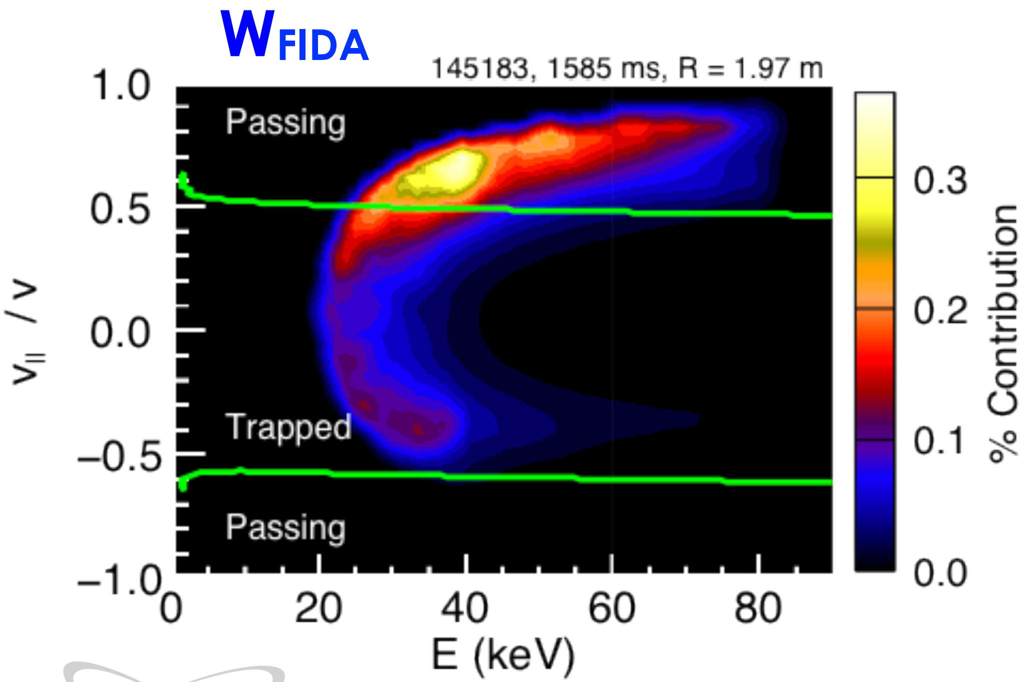


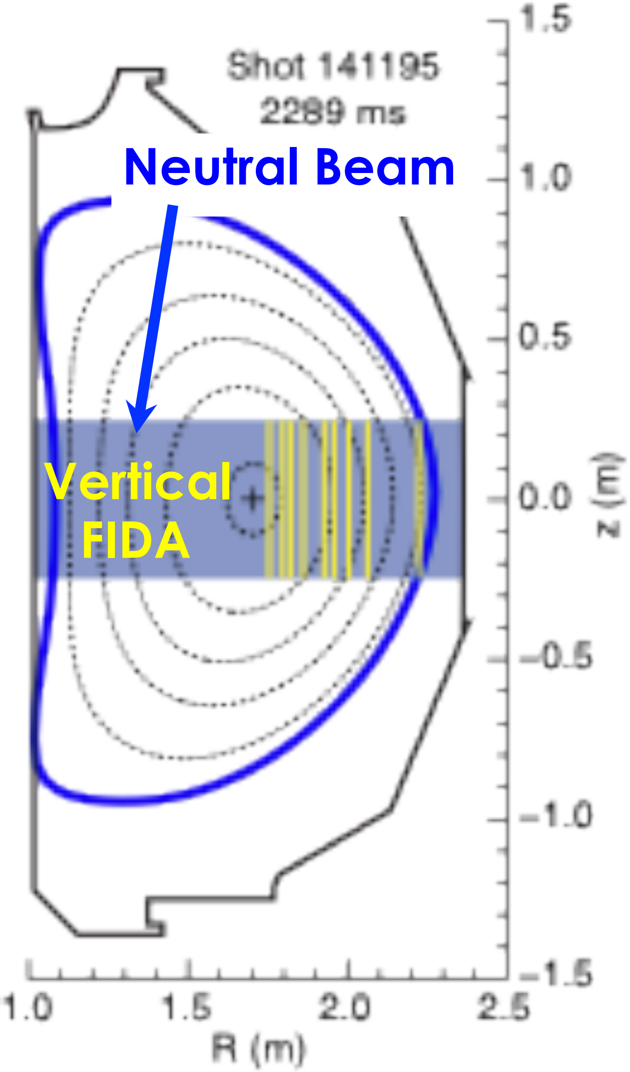
D_α Spectrum



FIDA System is Well Suited to Probing the Energetic Ion Distribution in NBCD Scenarios

- **Phase space weighting, W_{FIDA}, convolves instrument and atomic effects with the modeled F_{beam}**
- **$W_{FIDA}(R)$ is dominated by current-carrying ions**





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- **Experimental results and comparisons with modeling**
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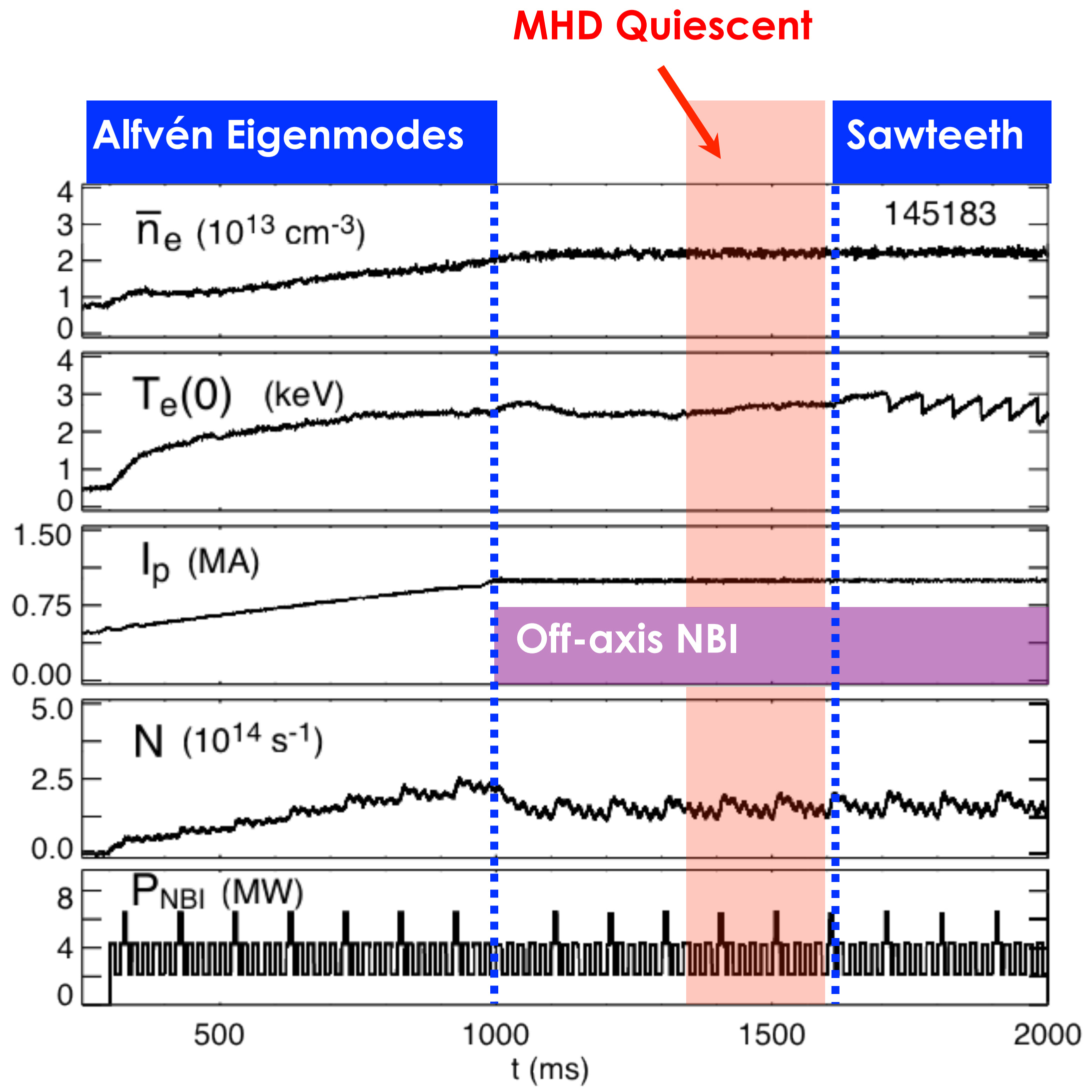
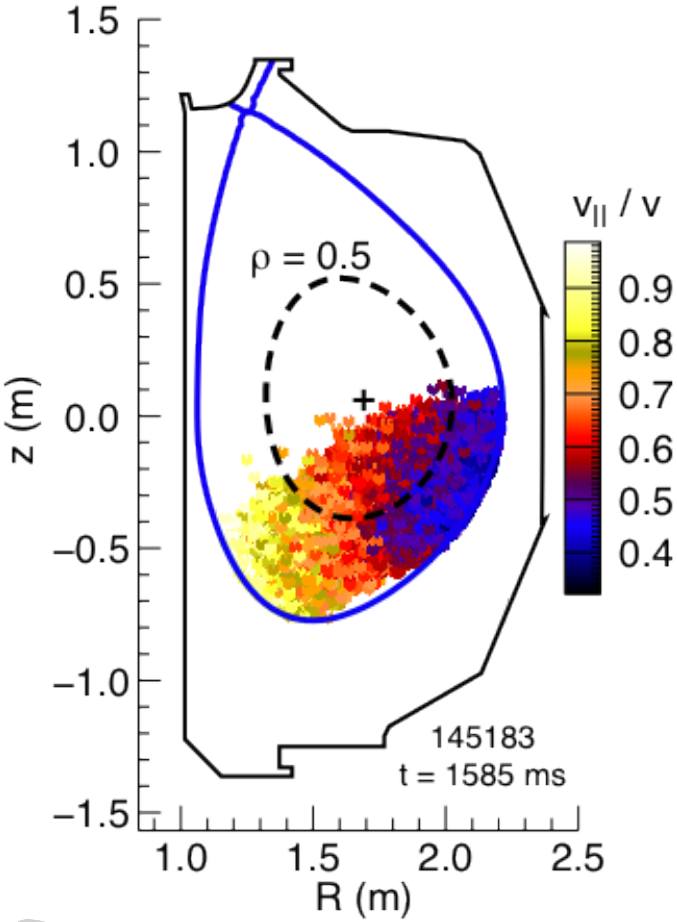
MHD Quiescent Plasmas are Designed to Isolate Energetic Ion Transport due to Microturbulence

- **L-mode Plasmas**: provide excellent diagnostic access
- **Current Ramp**: Alfvénic activity broadens the fast ion profile
- **Sawtooth Crashes**: redistribute fast ions and perturb equilibrium



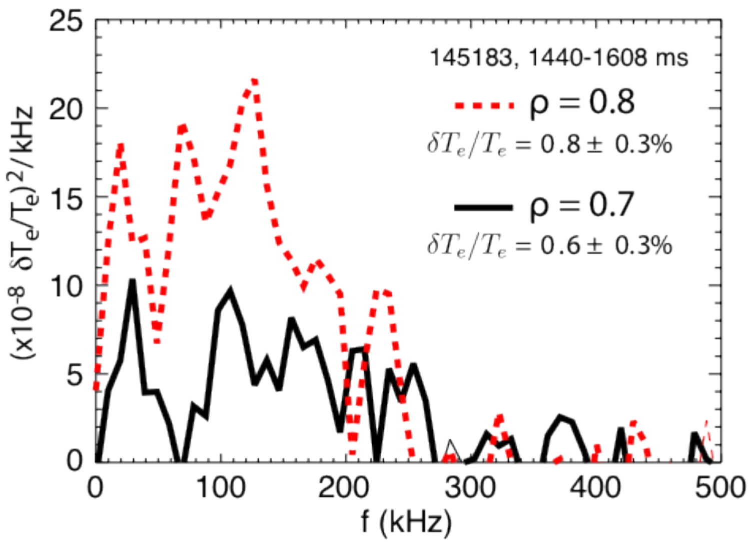
Off-axis Beam Injection Places the Energetic Ion Population in a Region of Large Turbulence Fluctuation Amplitude

- **Beam deposition is centered near ρ = 0.5**



- **Measured $\tilde{n}_e$ and $\tilde{T}_e$ are consistent with ion temperature gradient (ITG) type turbulence**

T_e Fluctuations



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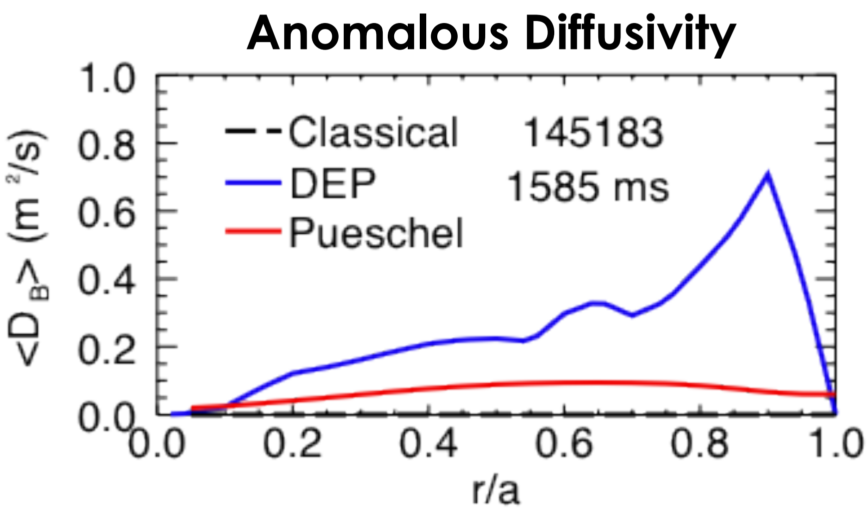
Turbulent Beam Ion Diffusivity is Calculated Using Two Independent Methods and Passed to NUBEAM

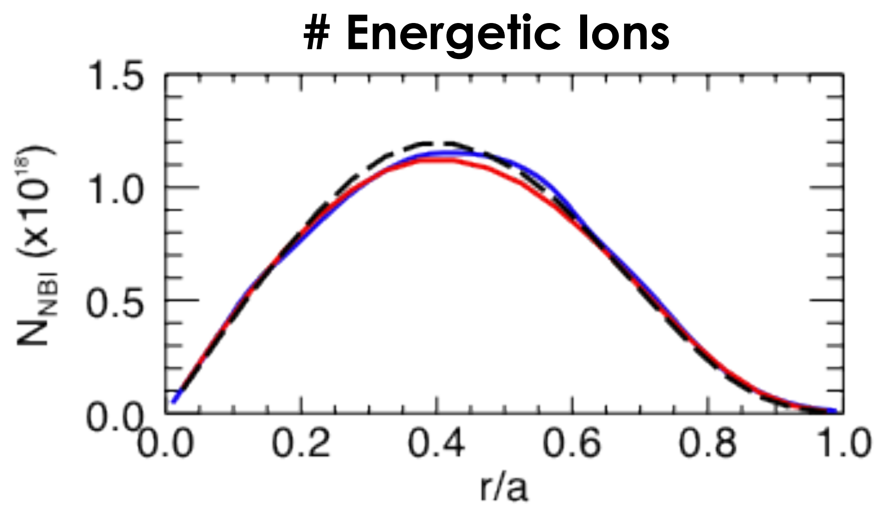
- **DEP[1]: quasilinear model**
  - TGLF[2] calculates mode frequencies, growth rates, and spectral weights
  - integrated into TRANSP/NUBEAM for self-consistent calculation of anomalous beam ion diffusivity, D_B

- **Pueschel[3]: analytic expressions, local value of D_B**

$$\frac{D^{\mathrm{es}}_{\mathrm{pass}}}{\chi_{\mathrm{eff}}} \approx \frac{0.292}{(v_{\|}/v)^2}\left(\frac{T_e}{E}\right)$$

$$\frac{D^{\mathrm{es}}_{\mathrm{trap}}}{\chi_{\mathrm{eff}}} \approx \frac{0.527\sqrt{\epsilon}}{(v_{\|}/v)(1-(v_{\|}/v)^2)}\left(\frac{T_e}{E}\right)^{3/2}$$



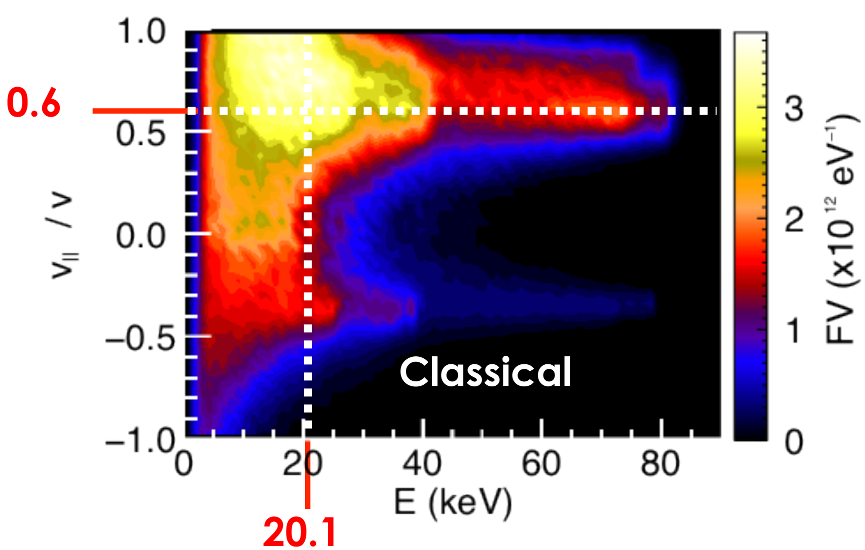


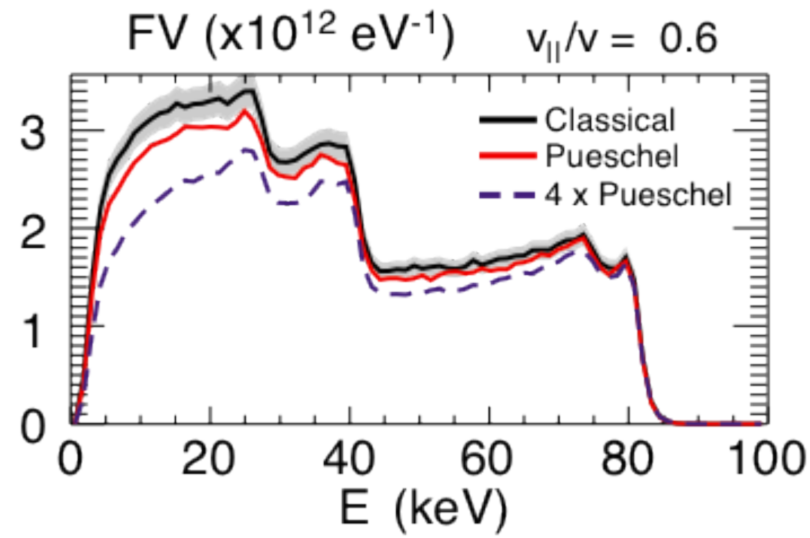
[1]Waltz, et al., *in preparation*
[2]Staebler, et al., *POP* **14**, 005909 (2007)
[3]Pueschel, et al., *NF* **52**, 103018 (2012)

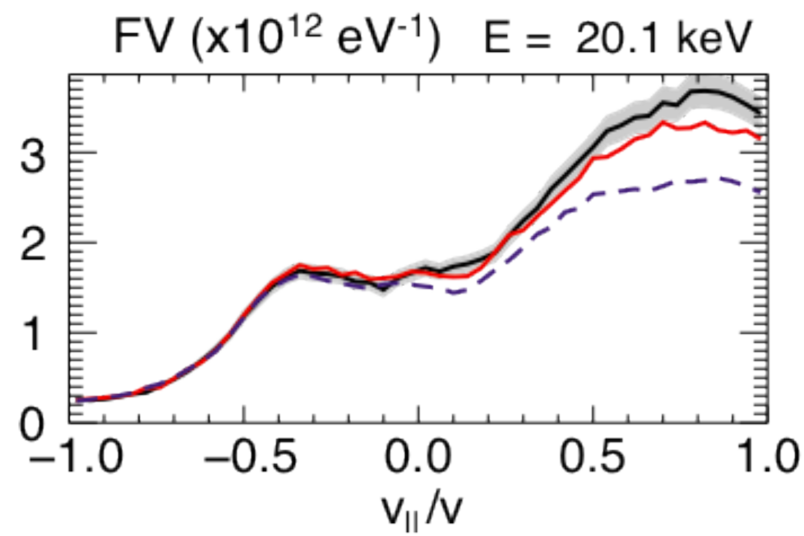
Qualitative Effects of Microturbulence are Demonstrated in NUBEAM Modeling

- **Example energetic ion distribution averaged over outer midplane, 0.44 ≤ ρ ≤ 0.64**

- **Transport increased at lower energies, as intended**







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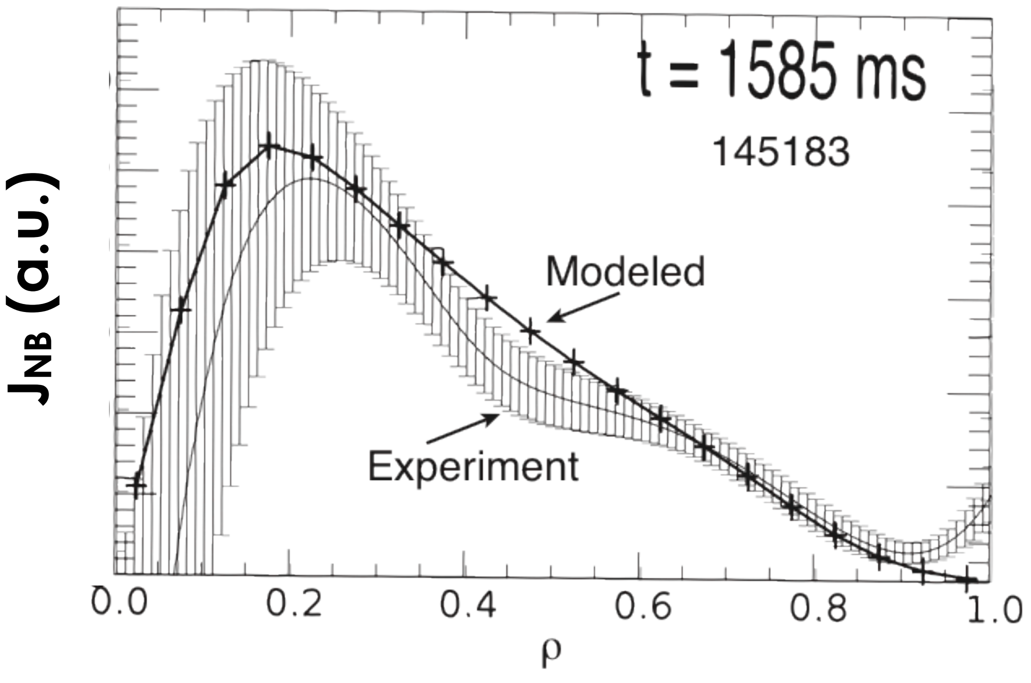
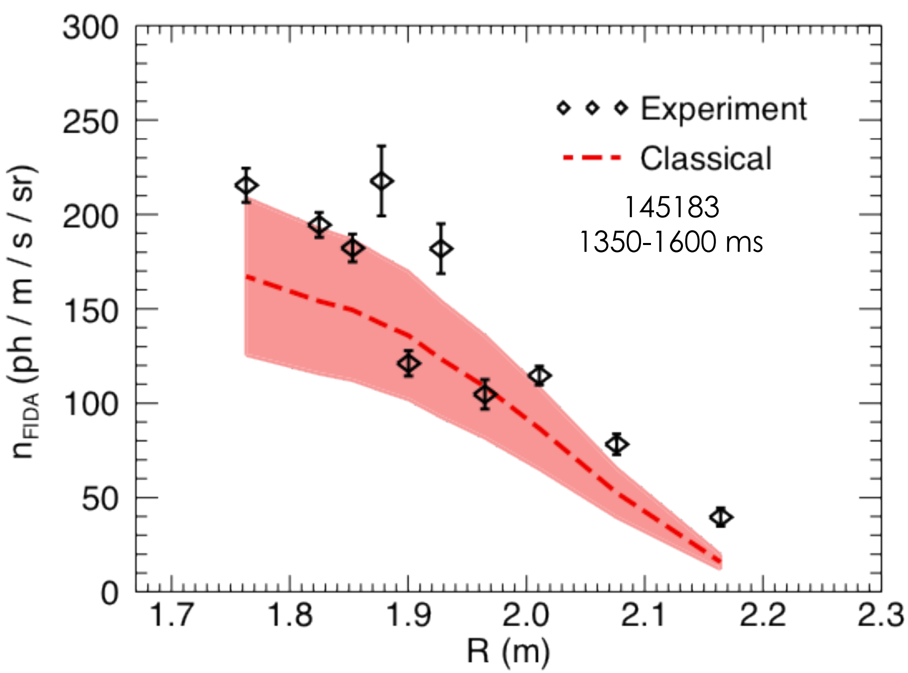
Neutral Beam Current Profile is Matched by Classical Fast Ion Transport Modeling (D_B = 0)



Measured Energetic Ion Profiles Feature Classical Shapes

- **FIDA density represents the energetic ion population within observed phase space**
  - Integrated over Doppler shifted energies of 20-40 keV
  - Shape is in excellent agreement with classical profile



- **FIDASIM* is a synthetic diagnostic incorporating sightline geometry, plasma profiles, and the energetic ion distribution**

*Heidbrink, et al., *CICP* **10**, 716 (2011)

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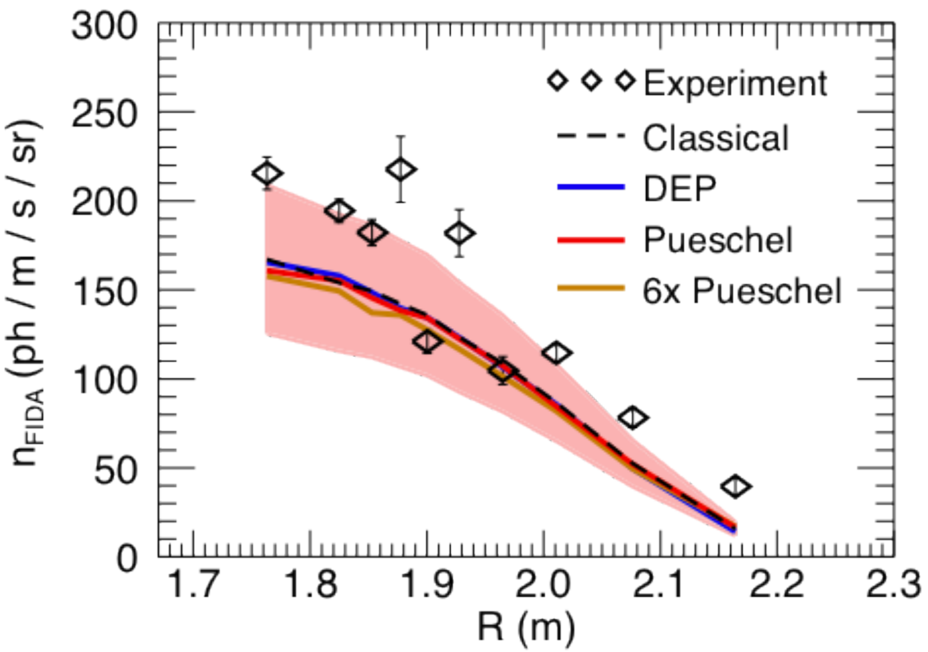
Modeled Effect of Energetic Ion Diffusion due to Microturbulence is too Small to Measure

- DEP and Pueschel profiles of D_B serve to change the simulated FIDA profile within the uncertainty range of NUBEAM

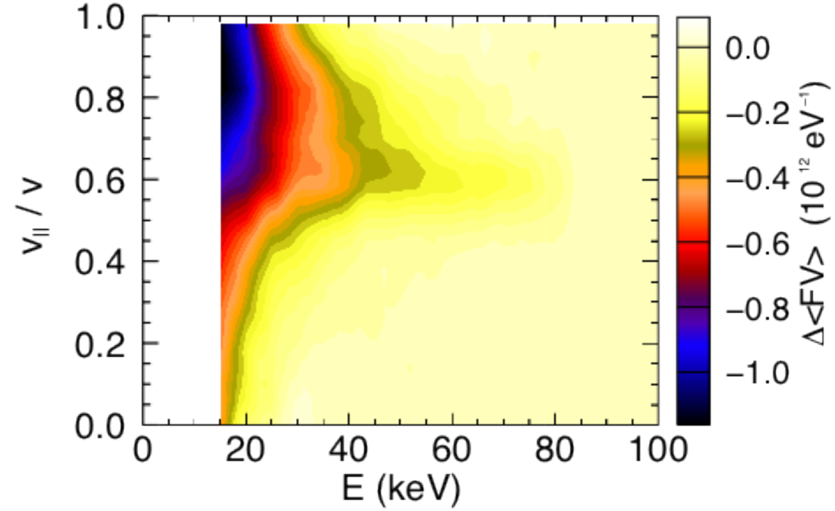
- Counter-intuitive result that the exaggerated case of D_B = 6 x Pueschel produces little effect

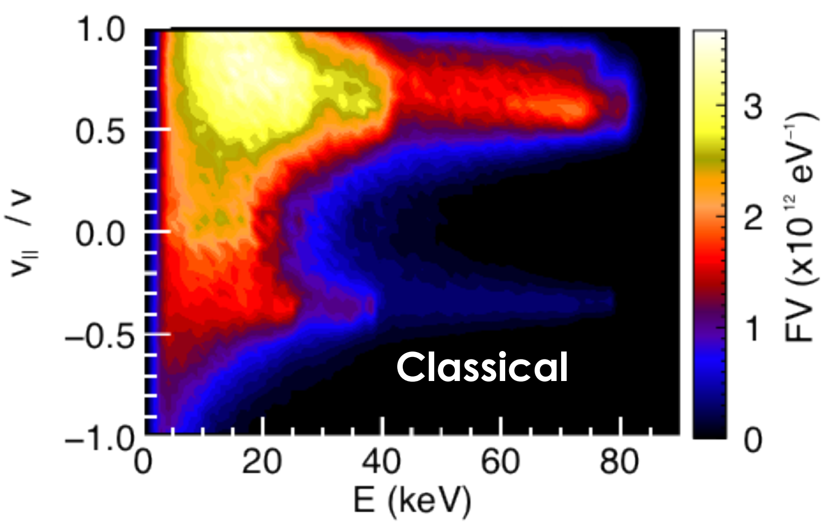


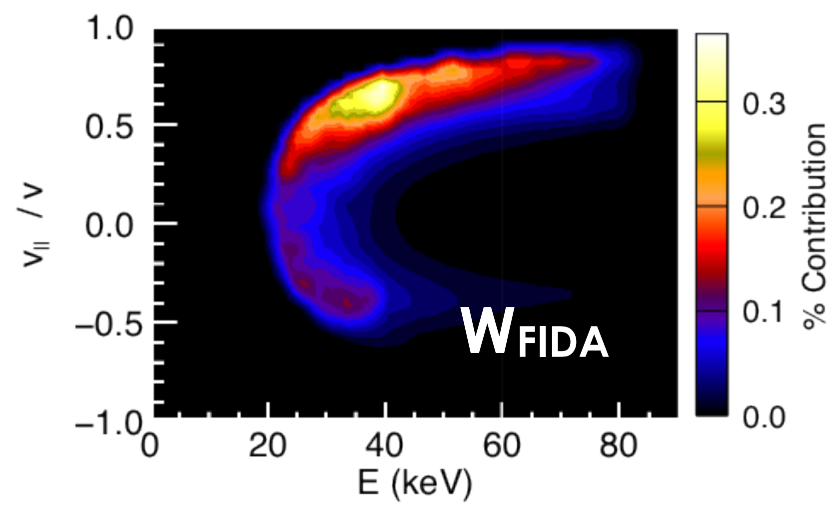
Turbulent Transport of Energetic Ions Occurs Outside of the FIDA and Current Drive Phase Spaces

- **Calculate the difference between the 4 x Pueschel and classical F_{beam}**
- **For this exaggerated effect, the transport is insignificant within the current drive energy range**

F_{beam} Differential







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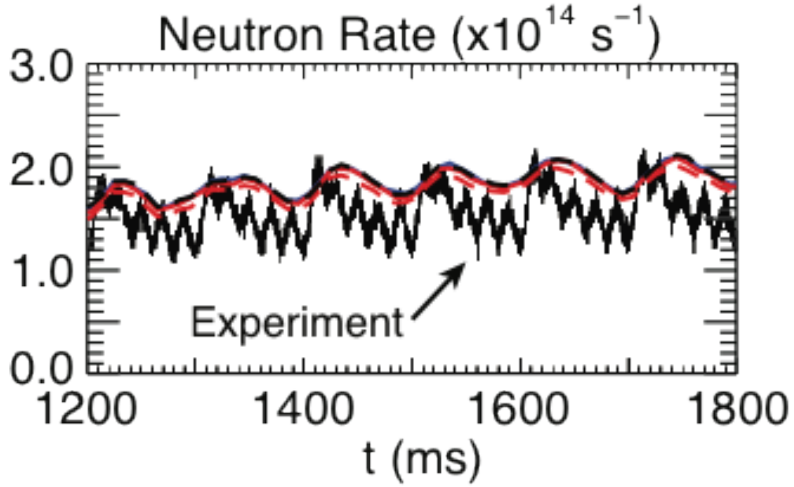
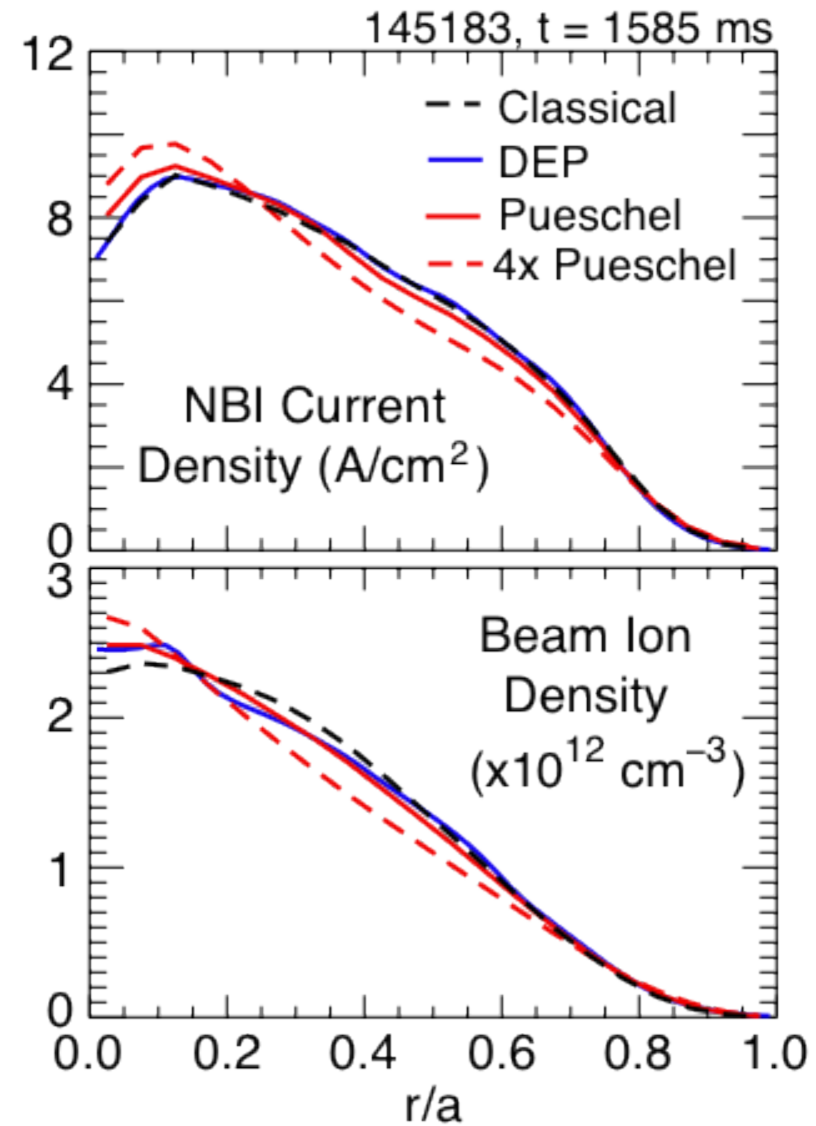
Diffusion in Off-axis Scenario Tends to Increase Core Beam Ion Density and Current Drive

- **Confinement improves as beam ions diffuse inward**
- **No effect on neutron rate**





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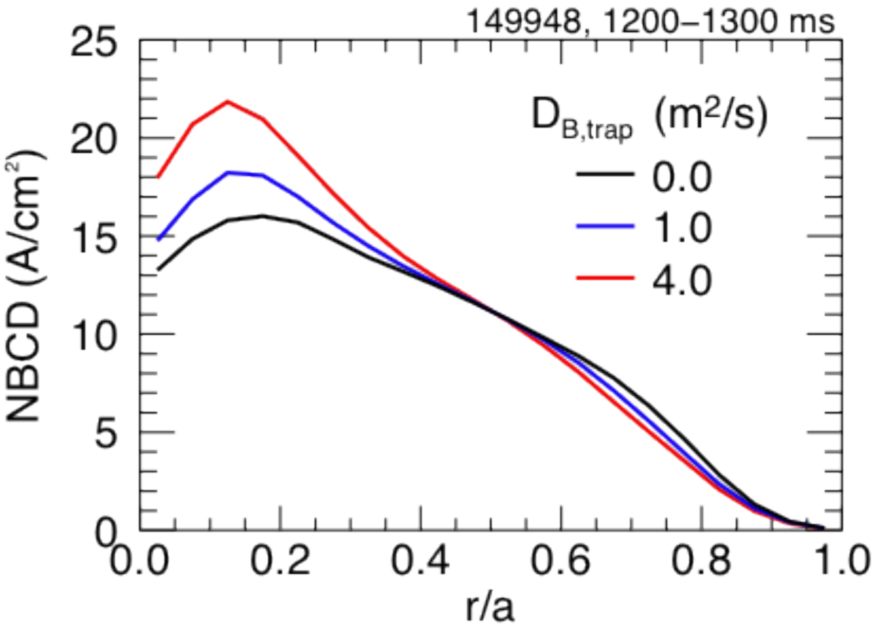
NUBEAM Anomalous Diffusivity Allows for Detailed Manipulation of the Energetic Ion Distribution

- **Case Study:**
  increase diffusion only for trapped ions

- **Beam-driven current increases with $D_{B,trap}$**
  - Appears that inward-diffusing trapped ions become passing
  - Total current drive increase is small, ~3%



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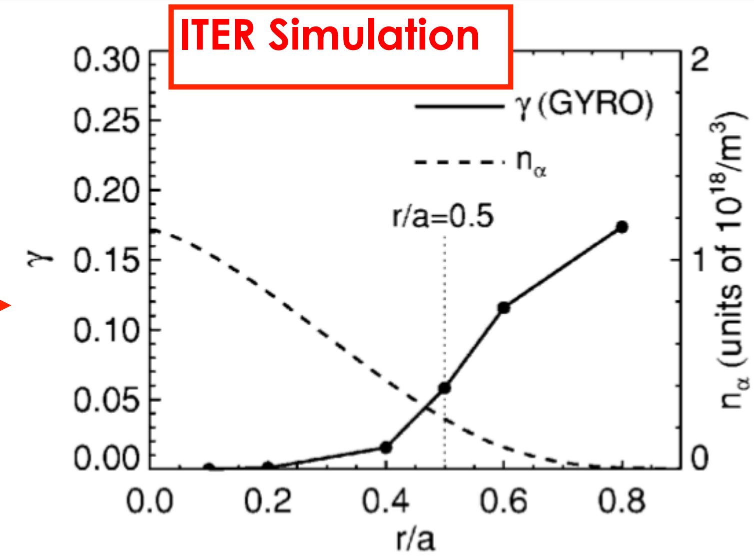
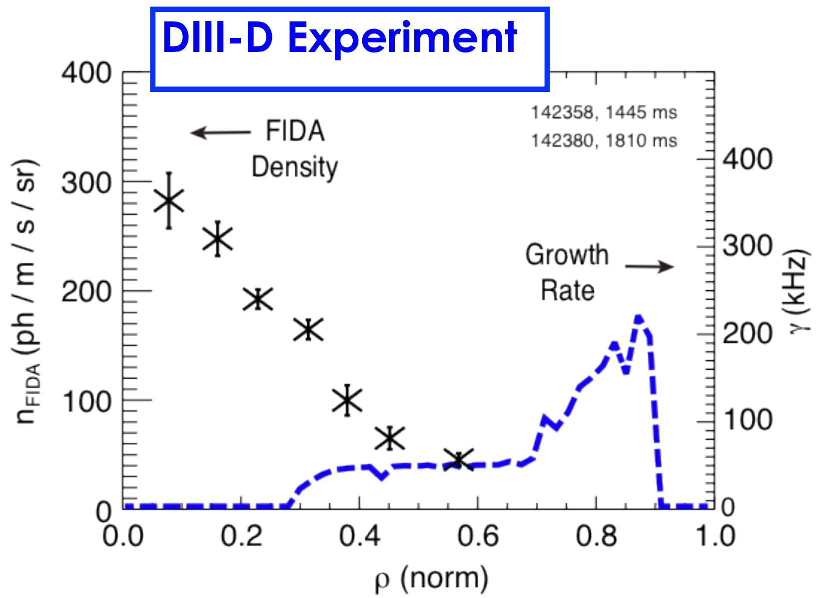
On-axis NBI Produces a Spatial Beam/Turbulence Overlap Similar to that Expected in ITER

- **Limited spatial overlap between fusion α-particles and turbulent fluctuations in ITER**
  Estrada-Mila, et al., *POP* **13**, 112303 (2006)

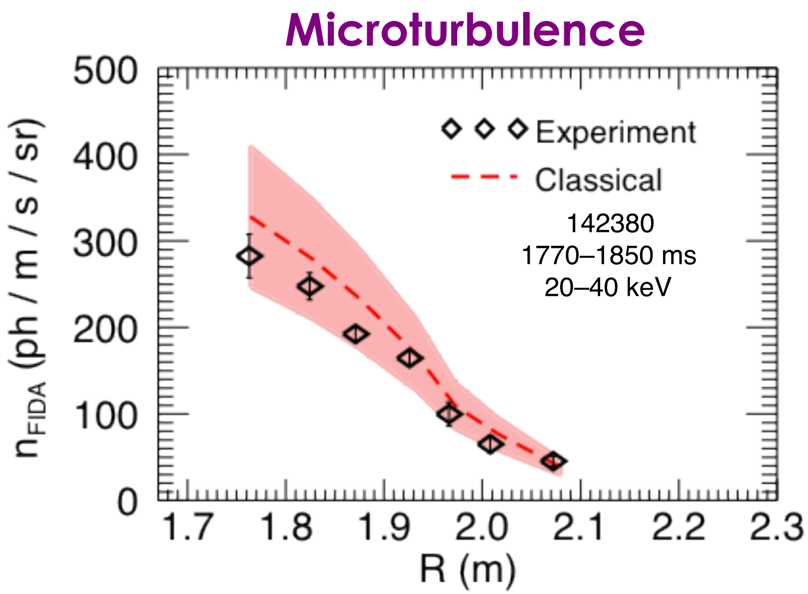


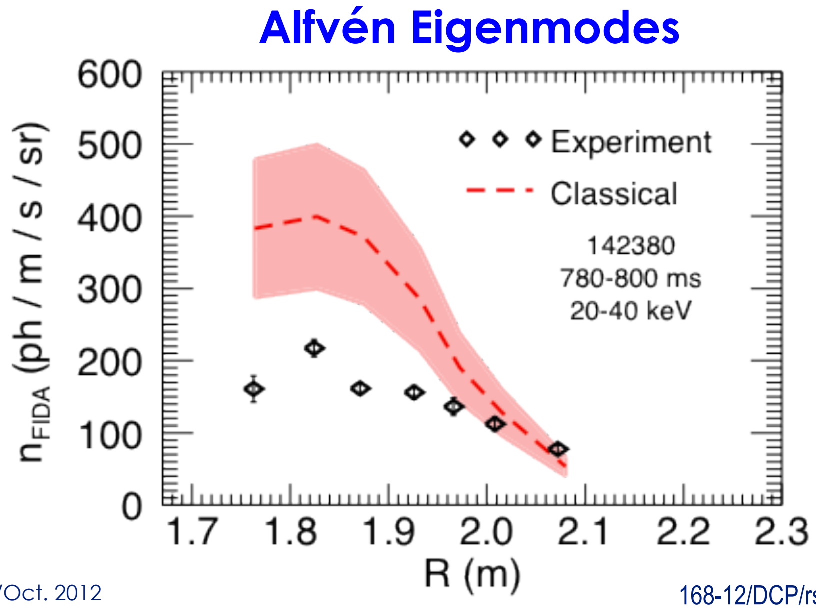
- **DIII-D on-axis beam injection**
  - Beam ion profile is peaked
  - Growth rate of the dominant turbulent mode (e.g., ITG) calculated by TGLF using measured plasma profiles



Energetic Ion Profiles are Classical in MHD-quiescent Plasmas Featuring High Levels of Thermal Plasma Turbulent Transport

- **Measured energetic ion profiles are consistent with classical transport expectations during microturbulence period**
- **Microturbulence characterized**
  - ITG-type dominate
  - $\tilde{n}/n$, $\tilde{T}_e/T_e \sim 1\%$
  - $\lambda_C > 2$ cm
- **FIDA profiles deviate significantly from classical expectation during Alfvénic activity**





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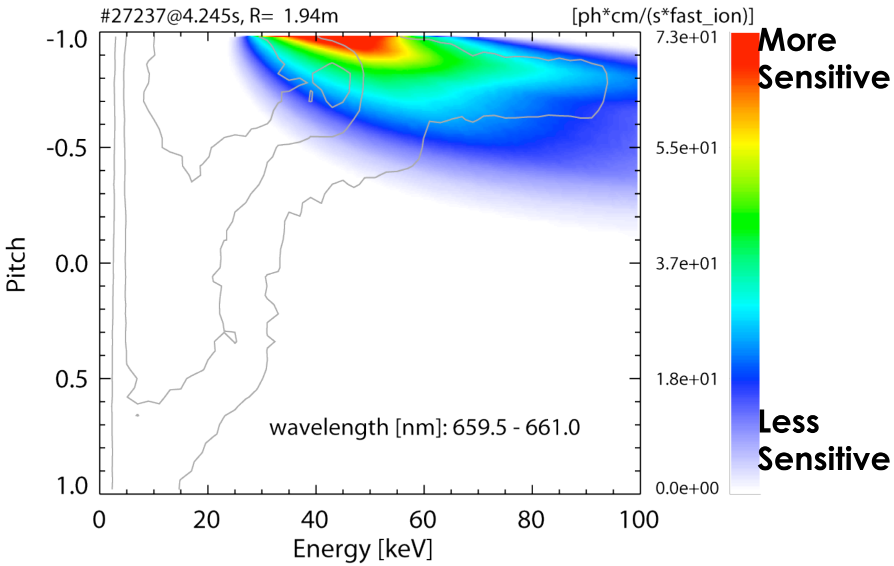
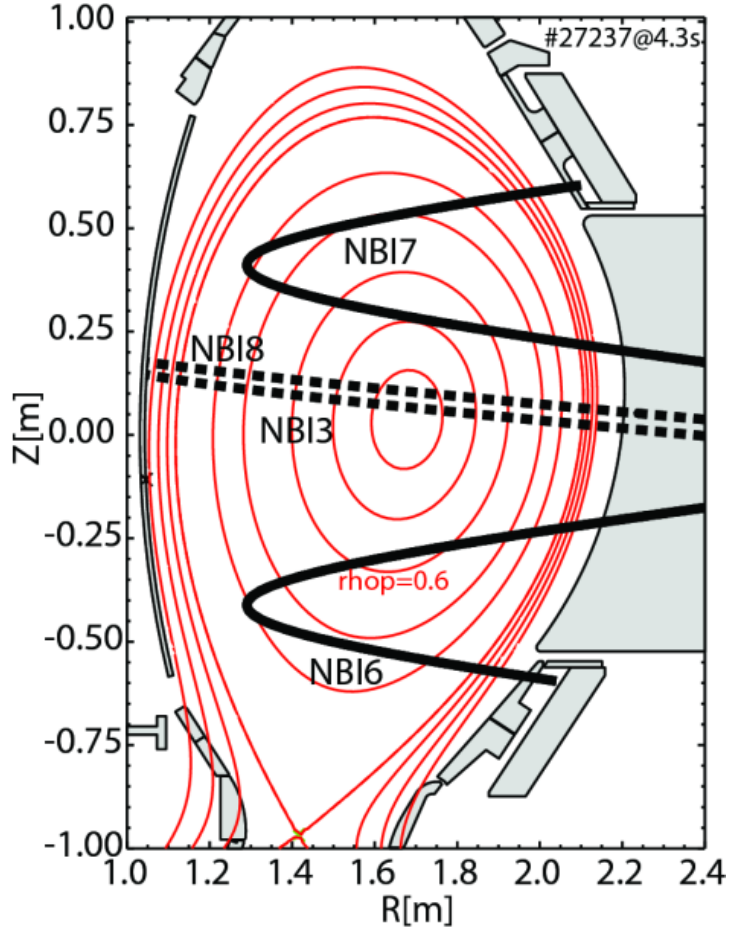
The ASDEX Upgrade Tokamak Features a FIDA System Well-suited to Off-axis Beam Current Drive Studies

- **Recently commissioned FIDA* system with 15 radially spaced channels**

- **Diagnostic weight function is sensitive to NBCD ions**



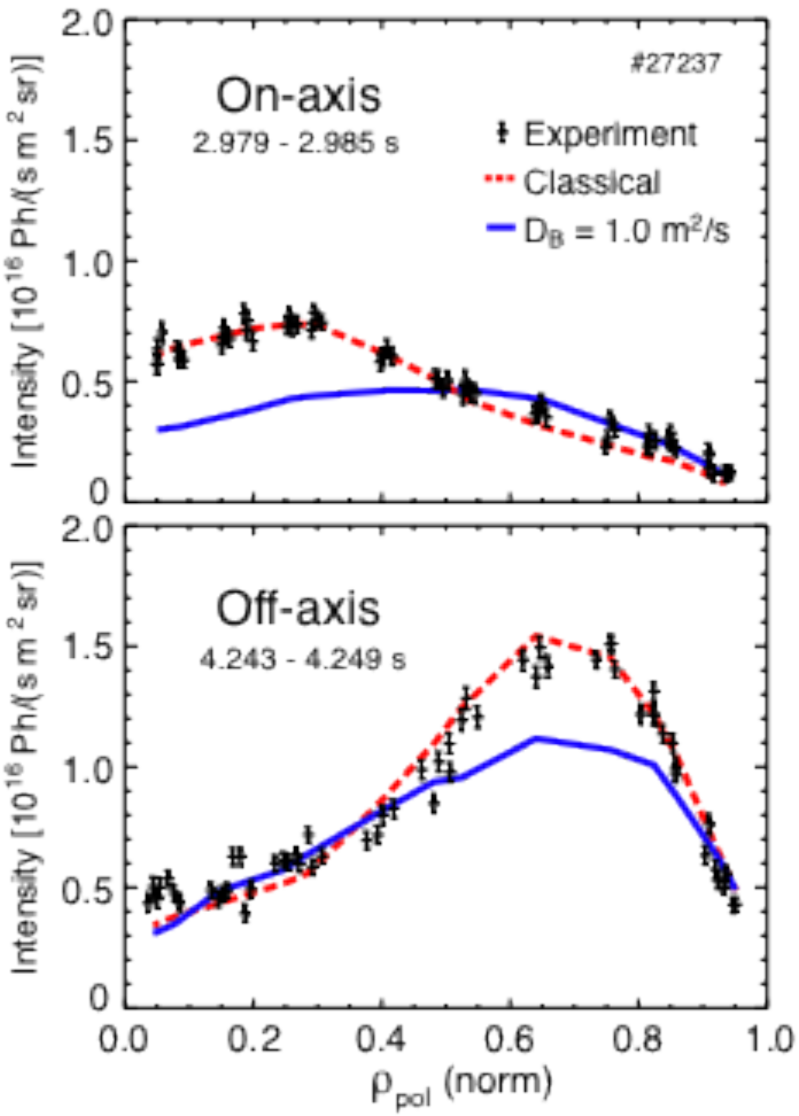
ASDEX Upgrade Beam Paths



*Geiger, et al., *PPCF* **53**, 065010 (2011)

ASDEX Upgrade Observes Classical Energetic Ion Profiles in Shots with 5 MW Beam Power Injected On-axis or Off-axis

- **Experimental analysis is similar to DIII-D case**
  - Synthetic diagnostic: F90FIDASIM
  - FIDA data integrated over 25 - 42 keV (659.5 - 661.0 nm)
- **Anomalous diffusion value is large: $D_B(R) = 1.0\ m^2/s$**



Experiments and Modeling Show that NBCD is Well Described in DIII-D, with Similar Expectations for ITER

- **Energetic ion transport is classical in well-documented, turbulent plasmas**
- **MHD-induced transport is more important for ITER**
- **New modeling tools allow for predicting energetic ion diffusion due to microturbulence**
- **Anomalous diffusivity term of NUBEAM continues to evolve, allowing for advanced modeling of energetic ion transport**
  - D_B : constant → $D_B(R, t)$ → $\mathbf{D_B(E, v_{||}/v, R, t)}$
  - **Alfvén eigenmodes**: energy and pitch dependence
  - **Edge magnetic perturbations**: strong spatial dependence