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

by


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Presented at the
54th Annual APS Meeting
Division of Plasma Physics
Providence, Rhode Island

October 29 — November 2, 2012
Concern for Turbulent Transport of Energetic Ions in ITER has Fluctuated Over Time

- **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 $\beta_\phi = 11\%$ shot demonstrated fusion product confinement most sensitive to MHD (Duong, NF 1993)
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Energetic Ion Transport by Microturbulence

Insignificant Significant

Theory: fusion $\alpha$-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


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

\[
D_B = \left( \frac{D_{EI}}{\chi_i} \right)_{\text{theory}} \chi_i,_{\text{exp}}
\]


- **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
Fast Ion Spectroscopy

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

- Off-axis beam injection and fast ion diagnostics in DIII-D

- 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
  - Determined from magnetic equilibria
  - Calculated using measured profiles [Sauter, Angioni, and Lin-Liu, POP 6, 2834 (1999)]

- Accurate Ohmic current profiles require excellent equilibria

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

Ferron, VI3.00002, Thursday Afternoon
Park, NO4.00013, Wednesday Morning

Park, et al., POP 16, 092508 (2009)
Fast Ion $D_\alpha$ (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

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

- Phase space weighting, $W_{\text{FIDA}}$, convolves instrument and atomic effects with the modeled $F_{\text{beam}}$

- $W_{\text{FIDA}}(R)$ is dominated by current-carrying ions
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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

![Graph showing Alfvén Eigenmodes, Sawteeth, and Off-axis NBI](image-url)
Off-axis Beam Injection Places the Energetic Ion Population in a Region of Large Turbulence Fluctuation Amplitude

- Beam deposition is centered near $\rho = 0.5$
- Measured $\tilde{n}_e$ and $\tilde{T}_e$ are consistent with ion temperature gradient (ITG) type turbulence

$\tilde{\rho} = 0.5$

$z$ (m)

$R$ (m)

$\frac{v_{||}}{v}$

$145183, 1440-1608$ ms

$\delta T_e/T_e = 0.8 \pm 0.3\%$

$\rho = 0.7$

$\delta T_e/T_e = 0.6 \pm 0.3\%$
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 \(D_B\)

\[
\begin{align*}
\frac{D_{\text{pass}}^{\text{es}}}{\chi_{\text{eff}}} & \approx \frac{0.292}{(v_\parallel / v)^2} \left( \frac{T_e}{E} \right) \\
\frac{D_{\text{trap}}^{\text{es}}}{\chi_{\text{eff}}} & \approx \frac{0.527 \sqrt{\epsilon}}{(v_\parallel / v)(1 - (v_\parallel / v)^2)} \left( \frac{T_e}{E} \right)^{3/2}
\end{align*}
\]

Anomalous Diffusivity

- Classical: 145183
- DEP: 1585 ms
- Pueschel

# Energetic Ions

1\(^{\text{Waltz, et al., in preparation}}\)
2\(^{\text{Staebler, et al., POP 14, 005909 (2007)}}\)
3\(^{\text{Pueschel, et al., NF 52, 103018 (2012)}}\)
Qualitative Effects of Microturbulence are Demonstrated in NUBEAM Modeling

- Example energetic ion distribution averaged over outer midplane, $0.44 \leq \rho \leq 0.64$

- Transport increased at lower energies, as intended
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)
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 \( D_B = 6 \times \text{Pueschel} \) produces little effect
Turbulent Transport of Energetic Ions Occurs Outside of the FIDA and Current Drive Phase Spaces

- Calculate the difference between the $4 \times$ Pueschel and classical $F_{\text{beam}}$

- For this exaggerated effect, the transport is insignificant within the current drive energy range
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
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** $D_{B,\text{trap}}$
  - 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 $\alpha$-particles and turbulent fluctuations in ITER

- 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
  – $\tilde{n}/n, T_e / T_e \sim 1\%$
  – $\lambda_c > 2 \text{ cm}$

• 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 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: $D_B(R) = 1.0 \text{ m}^2/\text{s}$
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 $\rightarrow D_B(R, t) \rightarrow D_B(E, v_{||}/v, R, t)$
  - **Alfvén eigenmodes**: energy and pitch dependence
  - **Edge magnetic perturbations**: strong spatial dependence