Fast-ion Profiles in DIII-D Discharges with Alfvén Eigenmode Activity

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AE activity has been observed to cause significant fast-ion transport

- Transport occurs when fast-ion orbits become stochastic
- Above threshold, fast-ion transport become stiff

Goal: Use FIDA to diagnose critical gradient behavior & validate models by comparing to:
- ‘classical’ (no AE transport) predictions
- predictions that model AE transport

[Collins et al, PRL 116 (2016)]
Outline

• How does FIDA measure fast ions
• Critical gradient experiments
  - Kick model validation
  - FIDA measurements of stiff transport
• Summary
Basics of Fast ion Dα (FIDA) Measurement

1. Fast ion charge exchanges with neutral (usu. from NBI)
2. Resulting fast neutral can change its atomic state through radiative decay or plasma collision
   - Emits visible Dα light via Balmer-α transition (n=3 to n=2 level, $\lambda_0 = 656.1$ nm) with a large Doppler shift (2–6 nm)
3. Photon is emitted within a few cm of initial charge exchange event
   - Intrinsic spatial resolution is < 2 cm

Relating Spectra to Fast-ion Distribution Function

- Measurement is the integral of the fast-ion distribution function with the diagnostic’s weight function (sensitivity in phase space)

\[ I(\lambda_1, \lambda_2, \phi) = \int \int \int f(E, p, x) W(\lambda_1, \lambda_2, \phi, E, p, x) \, dE \, dp \, dx \]

- A photon recorded at a particular wavelength can originate from fast-ions with various energies and pitch \( (p = \frac{v_{\parallel}}{v}) \)
Different Diagnostics Provide Comprehensive Survey of Fast-Ion Orbit Topology Space

**Neutral Particle Analyzer**

- Trapped fast ions: $|v_\parallel/\nu| < 0.3$

**Fast Ion Da Spectroscopy**

- Co-passing fast ions: $|v_\parallel/\nu| > 0.3$

**Neutron Diagnostic**

- High energy, volume-averaged
We Have Tools To Predict The Dα Spectrum

New FIDA software tools and OMFIT has streamlined the process of profile fitting, running TRANSP/FIDASIM, and comparison to data.
Critical Gradient Experiment: Use NBI Power Scan to Vary AE Activity

- Control AE activity with NBI power & geometry during the current ramp (reverse-shear, L-mode plasma)
Critical Gradient Experiment: Use NBI Power Scan to Vary AE Activity

- Control AE activity with NBI power & geometry during the current ramp (reverse-shear, L-mode plasma)
- Mode type/amplitude also varied with different beam geometry

Density Fluctuations

- #159243
  - 6.4 MW NBI
  - (log10(P^{1/2}))
- #159257
  - 3.7 MW NBI

- 400 600 800 1000
  - Time (ms)

AE Amplitude

- Avg. ECE AE Amplitude
  - (∑ΔTe / Te)
- Tang. NBI
- Mixed NBI
- Perp. NBI

Beam Power (MW)

- 2 4 6 8 10
AE Transport Has Been Simulated Using The Kick Model

- The ‘Kick Model’ is a time-dependent TRANSP simulation of AE transport. [M. Podestà, PPCF 56 (2014)]

- It uses AE structures computed by the linear ideal MHD code NOVA

- NOVA amplitudes are scaled to match experimental values based on ECE fluctuation measurements at a single timeslice. [Cheng, Chang, Phys. Fluids 29 (1986)] [Van Zeeland, Kramer, Austin et al., PRL 97 (2006)]
AE Amplitudes Are Time Evolved to Match Measured Neutron Rates

6.4 MW Tang. NBI
(used 8 RSAEs, 3 TAEs)

6.5 MW Perp. NBI
(used 5 RSAEs, 3 TAEs)

[C. Collins et al, NF 57 (2017)]
AEs Transport Fast Ions In The Part of Phase Space Measured By The FIDA Diagnostic

6.4 MW Tang. NBI
(used 8 RSAEs, 3 TAEs)
Kick Probabilities, #159243

6.5 MW Perp. NBI
(used 5 RSAEs, 3 TAEs)
Kick Probabilities, #162753
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The Kick Model Accurately Reproduces Fast Ion Profiles

6.4 MW Tang. NBI
Heidbrink et al., PoP 24 (2017)

6.5 MW Perp. NBI

• Kick model reproduces with FIDA, NPA, and neutron data, highlighting the importance of including energy and pitch dependence of the fast-ion distribution function in reduced models
The Kick Model Accurately Reproduces Fast Ion Profiles

6.4 MW Tang. NBI

Heidbrink et al., PoP 24 (2017)

6.5 MW Perp. NBI

Waltz et al., NF 55 (2015)

- Kick model reproduces with FIDA, NPA, and neutron data, highlighting the importance of including energy and pitch dependence of the fast-ion distribution function in reduced models.
Kick model shows AEs causes significant redistribution of beam ion density and current.

Hollow profile

Outward redistribution

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**NB Ion Density**

- Kick Model 162753P61
- Classical 159243Q71 (Tang. NBI)
- Classical 162753P10 (Perp. NBI)

**NB Current Density**

- Kick Model 159243R96
- Classical 159243Q71 (Tang. NBI)
- Classical 162753P10 (Perp. NBI)

Normalized Minor Radius ($\rho_N$)

Outward redistribution at t=800 ms
Threshold for Significant Transport is Beyond AE Linear Stability Threshold

[C. Collins et al, NF 57 (2017)]
Some AEs can be present without causing significant performance-degrading transport.

Are FIDA profiles also classical?

[C. Collins et al, NF 57 (2017)]
FIDA Profiles Measure Transport Threshold in Different Part of Phase Space

Redistribution from core to edge early in time

While neutrons are classical, FIDA is not
FIDA Behavior Was Also Studied in a High Beta-Poloidal Scenario

Example of Interesting High $\beta_p$ Discharge

- High $\beta_p$ scenario is a fully noninductive steady state discharge that is being explored for long-pulse tokamak operation
FIDA Behavior Was Also Studied in a High Beta-Poloidal Scenario

Example of Interesting High $\beta_p$ Discharge

- High $\beta_p$ scenario is a fully noninductive steady state discharge that is being explored for long-pulse tokamak operation

- Here, $\beta$ collapse is believed to be caused by $n=1$ external kink mode
High Beta-Poloidal Discharge Has Variety of AE Activity

Example of Interesting High $\beta_p$ Discharge

- $I_p$ (MA)
- $q_{min}$ (EFIT01)
- Density ($\times 10^{19} \text{m}^{-3}$)
- $T_{e\text{-core}}$ (keV)
- Normalized Beta

![Graphs and CO2 Interferometer Image]

- Shot #166489 CO2 Interferometer
- Log$_{10}(P^{1/2})$
- Measured/Expected Neutrons
- Time (ms)
- Non-classical fast-ions early
- Near-classical fast-ions late

DIII-D National Fusion Facility
FIDA Profiles Are Non-Classical Early In Time, Then Classical Later (Even With Many AEs Present)

Why is fast-ion confinement near-classical despite presents of multiple AEs?
Low Freq. Modes Present Early In Time When FIDA Is Not Classical

Strong, lower frequency mode activity is present early in time.
Internal Transport Barrier Leads To Reduced Fast-Ion Density Gradient

Internal Transport Barrier

Reduced Core $\tau_{SL}$

Reduced Fast-Ion Density Gradient

Classical fast-ion confinement

See also Holcomb et al, PoP (2015)
Goal: Use Reduced Models to Predict EP Transport & Optimize Scenarios for Future Fusion Reactors

- Reduced ‘critical gradient’ models aim to avoid detailed nonlinear calculations of saturated mode amplitudes.

Experiments guide model development:

1. Is an energy-dependent transport calculation necessary? **YES**
2. When does transport become stiff? **It varies in phase-space**
Summary

- The fast-ion Da (FIDA) diagnostic is an application of charge exchange recombination spectroscopy.
- Different fast-ion diagnostics measure different parts of the fast-ion distribution function.
- FIDA measurements agree with the kick model, showing that treatment of phase-space dependent transport is important for accuracy.
- Critical gradient transport threshold is beyond the AE linear stability threshold and is a phase-space dependent quantity.
Extra slides
Later Time Has Core localized TAEs

FIDA is classical at $t=3960$ ms
Early Time Has Both Core and Edge Modes

FIDA is not classical at \( t=2110 \) ms

Core localized TAEs

Edge modes/TAEs

shot #166489  CO2 Interferometer

\[ \log_{10}(P^{1/2}) \]

\[ f = 20-400 \text{ kHz} \]

\[ P \text{ (arb)} \]

\[ t=2110 \text{ ms} \]
Kick model shows AEs causes significant redistribution of beam ion density and current.
There Are Many Features In the Full Dα Spectrum

Active light contributions (due to NBI)

- Beam emission from excited injected neutrals (full, half, and third energies)
- Halo: charge exchange with bulk, thermal deuterium ions surrounding the beam
- FIDA-large Doppler shift 650-654 nm (10-60 keV)

Other contributions

- Visible bremsstrahlung emission
  \[ I_{\text{brem}} \propto n_e^2 Z_{\text{eff}} \frac{\lambda}{\sqrt{T_e}} \exp\left( \frac{-hc}{\lambda T_e} \right) \]
- Impurity lines
- Passive FIDA radiation (occurs without NBI)
- Cold edge Dα emission from cx with edge neutrals
A. Integrate net spectral radiance between wavelength (energy) range of interest to obtain FIDA intensity (good for comparing to FIDASIM simulation)

\[
\text{Radiance} \left( \frac{\text{ph}}{\text{s}-\text{m}^2-\text{sR-Å}} \right) \rightarrow \text{Intensity} \left( \frac{\text{ph}}{\text{s}-\text{m}^2-\text{sR}} \right)
\]

B. Divide by neutral beam pencil density to account for beam attenuation and geometry (good for comparing different shots)

\[
\rightarrow \text{‘FIDA density’} \quad n_{\text{FIDA}} \left( \frac{\text{ph}}{\text{s}-\text{sR}} \right)
\]

Integration range of 650.8-653.0 nm corresponds to line-of-sight energy range of 21-61 keV
FIDA Measurement: Collect Light, Disperse, and Take a Picture

- Usually use 1 ms integration time for good light collection
- New user-friendly data routines streamline analysis
Different fast ion diagnostics are more sensitive to different portions of velocity-space.

- **OBLIQUE FIDA**: More sensitive to co-passing fast ions ($p > 0.3$).
- **VERTICAL FIDA**: Trapped fast ions ($p < 0.3$).
- **SSNPA**: High energy, counter-passing ions ($p < -0.3$).
- **NEUTRONS**:
Fast-ion profiles in discharges with Alfvén eigenmode activity*

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In DIII-D, Alfvén eigenmode (AE) activity has been observed to cause significant fast-ion transport above a stochastic threshold that exceeds the linear threshold for AE stability [1]. Above threshold, transport becomes stiff, and fast-ion profiles measured by the fast-ion D-alpha (FIDA) diagnostic are virtually unchanged despite increased neutral beam drive. In order to pinpoint the onset of stiff transport, measured fast-ion profiles are compared with predicted profiles in the absence of AE-induced transport for several different experiments. In one experiment, multiple toroidal and reversed shear AEs create a hollow fast-ion profile [2]. Simulations with the TRANSP “kick” model that employ measured AE mode structures successfully reproduce the measurements [2]. In another experiment, the beam voltage is varied during the discharge at nearly constant beam power [3]. Variations in beam voltage alter the virulence of AE activity. In a third experiment, FIDA profiles are measured in high βₚ plasmas and compared with predicted profiles. Measuring the degree of fast-ion profile redistribution across a wide parameter regime is important for both transport model development and for designing scenarios that avoid undesirable AE-induced transport.

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