Alfvén eigenmodes (AE) degrade fast-ion confinement in high $\beta_N$, steady-state scenarios

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~ Fast-ion Transport

PNBI (MW)
Steady-state Advanced Tokamak (AT) scenarios often have elevated values of safety factor $q$.

- Projections predict a stable $\beta_N = 5$ steady-state scenario in DIII-D with increased ECCD and off-axis NBI.

1) Poli, NF 54 (2014)
2) Garofalo, NF 54 (2014)
3) Kessel, FED 80 (2006)

J.M. Park, APS (2013)
Many DIII-D discharges with $q_{\text{min}} > 2$ have poor global confinement

Is degraded fast-ion confinement the culprit?

$H_{89} = \frac{\tau_E}{\tau_{89}}$

Typical H-mode level

$H_{89} = E_{89}

1.0 1.5 2.0 2.5
2.6
2.4
2.2
2.0
1.8
1.6

$(2.7 < \beta_N < 3.9, \ 4.5 < q_{95} < 6.8)$

Ferron, PoP 20 (2013) 092504
1. AEs degrade fast-ion confinement in many steady-state scenario discharges
2. Degradation of fast-ion confinement can account for the overall degradation in global confinement
3. Physical mechanism of fast-ion transport: critical gradient behavior due to many wave-particle resonances
4. Outlook
Use TRANSP to quantify the degradation in fast-ion signals

- Use spatially uniform ad hoc fast-ion diffusion $D_f$ in TRANSP as an empirical measure of degraded fast-ion confinement
- Alternatively, use ratio of signal to “classical” prediction
- Global confinement varies with fast-ion confinement
The $q_{\text{min}} \sim 2$ discharge has more AEs and worse confinement than the $q_{\text{min}} \sim 1$ discharge.
Many Alfvén Eigenmodes are Observed & Expected

Measured Simultaneous Modes

Calculated Unstable TAE

Typical toroidal mode numbers: 2-5
$q_{\text{min}} \sim 1$ data agree with predicted fast-ion signals

**Ratio of signal to calculated predictions**

- Classical $\triangle$
- Neutrons $89\%$
- $W_{\text{fast}}$ $100\%$
$q_{\text{min}} \sim 1$ data agree with predicted fast-ion signals but $q_{\text{min}} \sim 2$ data do not.

**Ratio of signal to calculated predictions**

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<th>Classical</th>
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<tbody>
<tr>
<td>Neutrons</td>
<td>89%</td>
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<td>$W_{\text{fast}}$</td>
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Assuming fast-ion diffusion of 1.3 m²/s gives approximate agreement with qmin~2 data

Ratio of signal to calculated predictions

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<td>72%</td>
<td>108%</td>
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Degraded fast-ion signals correlate with increasing Alfvén eigenmode activity

- Every diagnostic that is sensitive to co-passing fast ions measures reductions
- The “AE Amplitude” is the average amplitude of coherent modes in the TAE band (from interferometer signals)
- Data from quasi-stationary portion of steady-state scenario discharges
Outline

1. AEs degrade fast-ion confinement in steady-state scenario discharges
2. Degradation of fast-ion confinement can account for the overall degradation in global confinement
3. Physical mechanism of fast-ion transport: critical gradient behavior due to many wave-particle resonances
4. Outlook
Enhanced fast-ion transport can explain the apparent reduction in thermal confinement at high $q_{min}$.

- Compare two matched discharges: $q_{min} \sim 1$ & $q_{min} \sim 2$
Enhanced fast-ion transport can explain the apparent reduction in thermal confinement at high $q_{\text{min}}$

- Compare power balance in $q_{\text{min}} \sim 2$ shot: Classical vs. $D_t = 1.3 \text{ m}^2/\text{s}$
- Reduced fast-ion stored energy
- Less power delivered to thermal plasma

$\Rightarrow$ Thermal diffusivities like $q_{\text{min}} \sim 1$ discharge
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Different combinations of on-axis & off-axis beams vary the fast-ion gradient that drives AEs

Use L-mode plasma in current ramp:
- Low AE threshold
- Well diagnosed
As predicted by linear AE stability theory, a steeper gradient drives more AE activity.

- Growth rate from TAEFL gyrofluid code
- GYRO gyrokinetic code gives similar results
Stronger AE activity causes a larger fast-ion deficit

- The measured neutron rate approaches the classical prediction for off-axis injection
The measured fast-ion profile is nearly the same for all angles of injection!

- Suggests the fast-ion transport is “stiff”
- The linear stability threshold acts (approximately) as a “critical gradient”

Of course, in quiet plasmas, the profiles differ.
A critical gradient model* reproduces the observed trend


Gorelenkov TH/P1-2
Recent Data Supports Critical Gradient Model of Alfven Eigenmode (AE) Induced Fast Ion Transport

- Beam power scan varies AE amplitude

- Modulated off-axis beam allows measurement of incremental fast-ion flux

- Local fast-ion density ceases to rise above certain input power/ AE amplitudes
  - SSNPA Neutral particle analyzer -> fast-ion density localized in phase space
Above threshold, the modulated signal is strongly distorted by AE transport.

- Conditionally average the modulated signal
- At low power, the signal agrees well with a classical model
- Classically, the amplitude of the modulated signal should increase at high power
Infer the fast-ion transport from a continuity equation for the measured “density”

- Define a “density” that incorporates the phase-space sensitivity $W$ in its definition

- Multiply the kinetic equation by $\int W \, d\tilde{v}$ to derive a fluid equation. Here, $S$ is the beam source and $n/\tau$ is the thermalization sink

- Linearize. Obtain a continuity equation for 1st order (modulated) quantities

- When the AEs are absent, the transport term is negligible $\rightarrow$ measure source in a low-power shot

- With AEs, use the measured $n$ to infer the divergence of the fast-ion flux
Divergence of fast-ion flux abruptly increases above an AE threshold → critical gradient behavior
Many small-amplitude resonances → “stiff” transport

- Use constants-of-motion to describe complex Energetic Particle orbits

![Graph showing magnetic moment vs. toroidal canonical angular momentum with color-coded regions for trapped, lost, co-pasing, and count passing particles.](image-url)
Many small-amplitude resonances → “stiff” transport

- Injected beams populate the co-passing & trapped portions of phase space
Many small-amplitude resonances $\rightarrow$ “stiff” transport

- Use measured modes to compute orbits that satisfy a resonance condition
- Many resonances cause stochastic overlap in phase space*

*White, PPCF 52 (2010) 045012
The high $q_{\text{min}}$ steady-state scenario plasmas also have many resonances.

$q_{\text{min}} \sim 2$

$q_{\text{min}} \sim 1$

Resonance Deposition

Toroidal Canonical Angular Momentum

Magnetic Moment ($\mu B/E$)
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New strategies are needed to overcome critical gradient behavior

Above AE stability threshold, additional on-axis beam power is ineffective

- More off-axis beam power (broader beam profile) 
  *Nucl. Fusion 53 (2013) 093006*
- Better thermal confinement (less auxiliary power for same $\beta_N$) 
  *PPC/P2-31, EX/P2-39*
- Replace beam-driven current with RF 
  *TH/P2-38*
- Modify AE stability 
  *Nucl. Fusion 49 (2009) 065003*
Conclusions

1. AEs degrade fast-ion confinement in many steady-state scenario discharges

2. Degradation of fast-ion confinement can account for the overall degradation in global confinement

3. Physical mechanism of fast-ion transport: critical gradient behavior due to many wave-particle resonances
Backup Slides
Implications for ITER

- ITER steady-state scenario is predicted to have unstable AEs
- Multiple modes with many resonances are likely → critical gradient fast-ion transport regime
- Not strongly driven past threshold
- Critical gradient calculation predicts modest effect
High $\beta_N$, high $q_{\text{min}}$ discharges with good fast-ion confinement are observed.

- Less Beam Power
- Higher Density
  $\Rightarrow$ Weaker AE Drive