Predictions of alpha-particle and neutral-beam heating and transport in ITER scenarios

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Acknowledgements: G. M. Staebler (GA), He Sheng (PKU)

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I. Introduction: Energetic Particle (EP) transport by Alfvén eigenmodes (AEs) and the need for reduced models

II. TGLFEP + ALPHA code: A flexible and inexpensive 1D EP transport model

III. Predictions for ITER scenarios for burning plasmas with beam heating

IV. Summary
Main takeaway: The local critical-gradient model (CGM) of AE transport of EPs shows redistribution from mid to outer core in ITER.

Mid-core AEs redeposit EPs to the outer radii where their energy is absorbed.

Time-averaged EP density profile corresponds directly to the heating profile.
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EP transport by so-called “Alfvén eigenmodes” (AEs) can be very complicated

A quick primer on EP-transport jargon:
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AEs drive most EP transport, mainly in the particle channel (i.e. transport is convective).
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EPs have large orbits relative to thermal species, leading to:

- thermal gradients
- microturbulence
- EP gradient
- AEs

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DIII-D TAE with EP orbits

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So how dangerous are EP-driven AEs in ITER and other devices?

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So how dangerous are EP-driven AEs in ITER and other devices?

It’s complicated!

EPs have large orbits relative to thermal species, leading to:
- Sparse spectrum and high coherency
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- EPs have large orbits relative to thermal species, leading to:

We need reduced models to get useful transport estimates.

Here, we focus on the ALPHA critical-gradient model, probably the simplest and most nimble in use.
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The 1D ALPHA EP density transport code uses the stiff critical gradient model based on local nonlinear 2010 GYRO simulations

\[
\frac{\partial n_{EP}}{\partial t} = S \left( 1 - \frac{n_{EP}}{n_{SD}} \right) - \nabla \cdot \Gamma_{EP} \rightarrow 0
\]

ALPHA code provides source parameters and finds time-invariant solution.

\(^1\)E.M. Bass and R.E. Waltz, PoP 17 112319 (2010)
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fusion or beam source

\(\nabla \cdot \Gamma_{EP} \rightarrow 0\)

slowing-down sink (plasma heating)

**Diffusive EP flux:**

\[
\Gamma_{EP} = - \left( D_{\text{micro}} + D_{AE} \right) \nabla r n_{EP}
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classical slowing-down density

Gaffey 1976

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**most unstable \( n \) critical gradient**

**stiff AE transport**

### ALPHA code provides source parameters and finds time-invariant solution.

\( \Gamma_{EP} = - \left( D_{micro} + D_{AE} \right) \nabla_r n_{EP} \)

\( D_{micro} \) is the effective background diffusion coefficient from the Angioni quasilinear model\(^2\) fit to GYRO.

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Critical gradient as a function of \(r\) determined by TGLFEP, the crucial input.

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Fusion or beam source

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Gaffey 1976

Most unstable \(n\) critical gradient

Turbulence

Classical slowing-down density

Fusion source

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Gaffey 1976

**AE transport level is part of solution**

\[
D_{\text{micro}} + D_{AE} (\text{AU})
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**Critical gradient** as a function of \(r\) determined by TGLFEP, the crucial input.

**Boundary condition:** Edge \(n_{EP}\) is set to zero (pessimistic edge loss estimate).

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TGLFEP code uses the gyro-Landau fluid TGLF model to find the AE-EP critical gradient where $\gamma_{AE} \rightarrow 0$.

Using a high-temperature equivalent Maxwellian, TGLF (gyro-Landau fluid) matches GYRO (gyrokinetic) AE growth rates well, but is \textbf{>100 times cheaper}.

\cite{He2017}
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\textbf{TGLFEP}\textsuperscript{1}: A parallelized wrapper that searches across mode number and drive strength for the critical gradient.

\textsuperscript{1}He Sheng, R.E. Waltz, and G.M. Staebler, PoP \textbf{24}, 072305 (2017)
The model is extended to include simultaneous drive of multiple EP species

The multi-species criticality condition (in terms of each EP pressure $p_i$) appears as a weighted sum.

\[ \sum_i \frac{dp_i}{dr} \geq (dp_i/dr)_{\text{crit}} \]

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The two isolated critical gradients specify the two-species critical gradient for coupled transport.

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In other words: AEs driven by NBI ions drive additional alpha particle transport, and vice versa.

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Outline

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We consider a 30 MW $Q \approx 10$ ITER profile prediction based on EPED1 and tGYRO TGLF core transport\(^1\)

\[ n_{i,e} \]

\[ n_{\text{alpha,SD}} \]

\[ n_{\text{NBI,SD}} \]

\[ 100n \]

\[ r/a (\text{to pedestal top}) \]

\(^1\) J. Kinsey, G.M. Staebler, J. Candy, R.E. Waltz, and R. Budny, Nucl. Fusion 51, 083001 (2011)
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\[ n_{i,e} \]

\[ n_{\alpha,SD} \]

\[ T_e \]

\[ T_i \]

\[ 0.01T_{\alpha} \]

\[ 0.05T_{NBI} \]

\[ 20n_{NBI,SD} \]

\[ 100n_{\alpha,SD} \]

\[ n \left(10^{19}/m^3\right) \]

\[ r/a \text{ (to pedestal top)} \]

\[ T \text{ (keV)} \]

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**Figure 1:**
- Left panel: Profile of $n_{i,e}$, $20n_{\text{NBI,SD}}$, and $100n_{\alpha,\text{SD}}$.
- Right panel: Plots of $T_e$, $T_i$, $0.05T_{\text{NBI}}$, $0.01T_{\alpha}$.

**EP $\beta$ fraction of about 30% → AEs robustly unstable.**

**Very weak central shear region (from sawtooth current mixing) proves to be the most AE unstable for the base case scenario with maximum current drive and current penetration.**

---

\(^1\) J. Kinsey, G.M. Staebler, J. Candy, R.E. Waltz, and R. Budny, Nucl. Fusion 51, 083001 (2011)
As in 2015 GYRO ITER simulations\textsuperscript{1}, TGLFEP finds unstable AEs only in the mid core where $-\frac{dn}{dr_{SD}} > -\frac{dn}{dr_{\text{crit}}}$.

\begin{figure}
  \centering
  \includegraphics[width=\textwidth]{ITER_base_case}
  \caption{ ITER base case}
\end{figure}

\textsuperscript{1}R.E. Waltz, E.M. Bass, W.W. Heidbrink, and M.A. VanZeeland, Nucl. Fusion \textbf{55}, 123012 (2011)
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\[\text{Alpha particles} \]

\[\text{ITER base case} \]

\[\text{NBI ions} \]

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\[\frac{dn}{dr_{SD}}\]

\[\frac{dn}{dr_{crit}}\]

Alpha particles

**ITER base case**

Nominally unstable region

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\[\frac{dn}{dr_{SD}}\]  
\[\frac{dn}{dr_{crit}}\]

Alpha particles

Nominally unstable region

Transport of EPs by background processes, through Angioni quasilinear ratio \(\chi_{EP}/\chi_i\), depletes core into the “hole” made by CGM AE transport.

Coupled alpha and NBI drive nearly doubles confinement loss from mid core. Net edge loss is small!

- Classical Alphas volume-integrated birth rate
- Classical NBI volume-integrated birth rate
- NBI particle flow
- Classical Alphas density
Coupled alpha and NBI drive nearly doubles confinement loss from mid core. Net edge loss is small!

\( n (10^{19}/m^4) \)

Alphas

classical

self

Net edge loss is small!

\( n (10^{19}/s) \)

particle flow

volume-integrated birth rate

self

Each EP species drives only its own transport
Coupled alpha and NBI drive nearly doubles confinement loss from mid core. Net edge loss is small!

Mid-core AEs redeposit EPs outward

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EPs redistributed from **inner core to outer core**
- alphas
- NBI ions

**self:** 14.1% 23.1%
Coupled alpha and NBI drive nearly doubles confinement loss from mid core. Net edge loss is small!

Mid-core AEs redeposit EPs outward

**self:** Each EP species drives only its own transport

**coupled:** Simultaneous drive transports both species.

EPs redistributed from **inner core to outer core**

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Outside AE-unstable region (center and edge) flux comes from background transport component.

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EPs redistributed from *inner core to outer core*

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$$n \left(10^{19}/m^4\right)$$

$$\text{classical}$$

$$\text{volume integrated birth rate}$$

$$q$$

$$r/a$$

Base case
High $q$ and low shear are destabilizing, but shear is more important

**Steady-state** (non-inductive current drive) case has 7.5 MA (half base-case value) current and weak penetration.
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I. Introduction: Energetic Particle (EP) transport by Alfvén eigenmodes (AEs) and the need for reduced models

II. TGLFEP + ALPHA code: A flexible and inexpensive 1D EP transport model

III. Predictions for ITER scenarios for burning plasmas with beam heating

IV. Summary
Summary:
TGLFEP+ALPHA reduced model code ITER predictions

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- Reductions in ITER current (increased $q$) or current penetration (increased $q_{\text{min}}$ with lower core shear) increase mid-core confinement loss.

- Tailoring the current profile to raise central-core shear offers a promising control knob for **reducing AE-driven mid-core EP confinement losses in ITER**.

**Going forward:**

- Estimation of **mode intermittency**, needed to predict peak heat flux (instead of time average)

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The ALPHA model neglects much physics but retains experimental relevance.

A DIII-D tilted NBI experiment\(^1\) moving the NBI from on-axis to off-axis had virtually no effect on the measured beam ion profile.

EP pressure profile prediction from the ALPHA critical-gradient model is well validated by experiment\(^1\) and verified against nonlinear GYRO simulations\(^2\).

\(^1\)R.E. Waltz and E.M. Bass, Nucl. Fusion 55 123012 (2015)
The AE stiff-transport critical gradient can be identified with a simple linear stability condition

A careful nonlinear, gyrokinetic study (using GYRO) of DIII-D discharge 146102 shows runaway over a critical EP gradient\(^1\).

\(\gamma_{AE-ITG/TEM}\)
- EP+thermal drive on AEs

\(\gamma_{AE}\)
- only EP drive on AEs

\(\gamma_{ITG/TEM}\)
- leading microturbulent growth rate

Runaway onset at \(\gamma_{AE+ITG/TEM} = \gamma_{ITG/TEM}\) is due to suppression of AEs by microturbulence-driven zonal flows.

By luck, the much simpler condition \(\gamma_{AE} = 0\) works just as well, allowing us to take microturbulence out of the critical gradient analysis (but not transport).

\(^1\)Bass and Waltz, PoP 24, 122303 (2017)
Inexpensive, automated TGLFEP confirms shear and elongation are stabilizing, higher $q$ is destabilizing.

The linear stability threshold (synonymous with the critical gradient absent thermal drive) spans at least three orders of magnitude for experimentally relevant parameters.

Empirical scaling of the critical EP gradient:\footnote{He Sheng et al., PoP 24, 072305 (2017)}

$q$ profile dependence

Stronger elongation is also generally stabilizing.

But... Most transport occurs at very low shear, where $q$ scaling is much weaker.

We will see that the $q$ profile matters surprisingly little in practice.