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

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# Outline

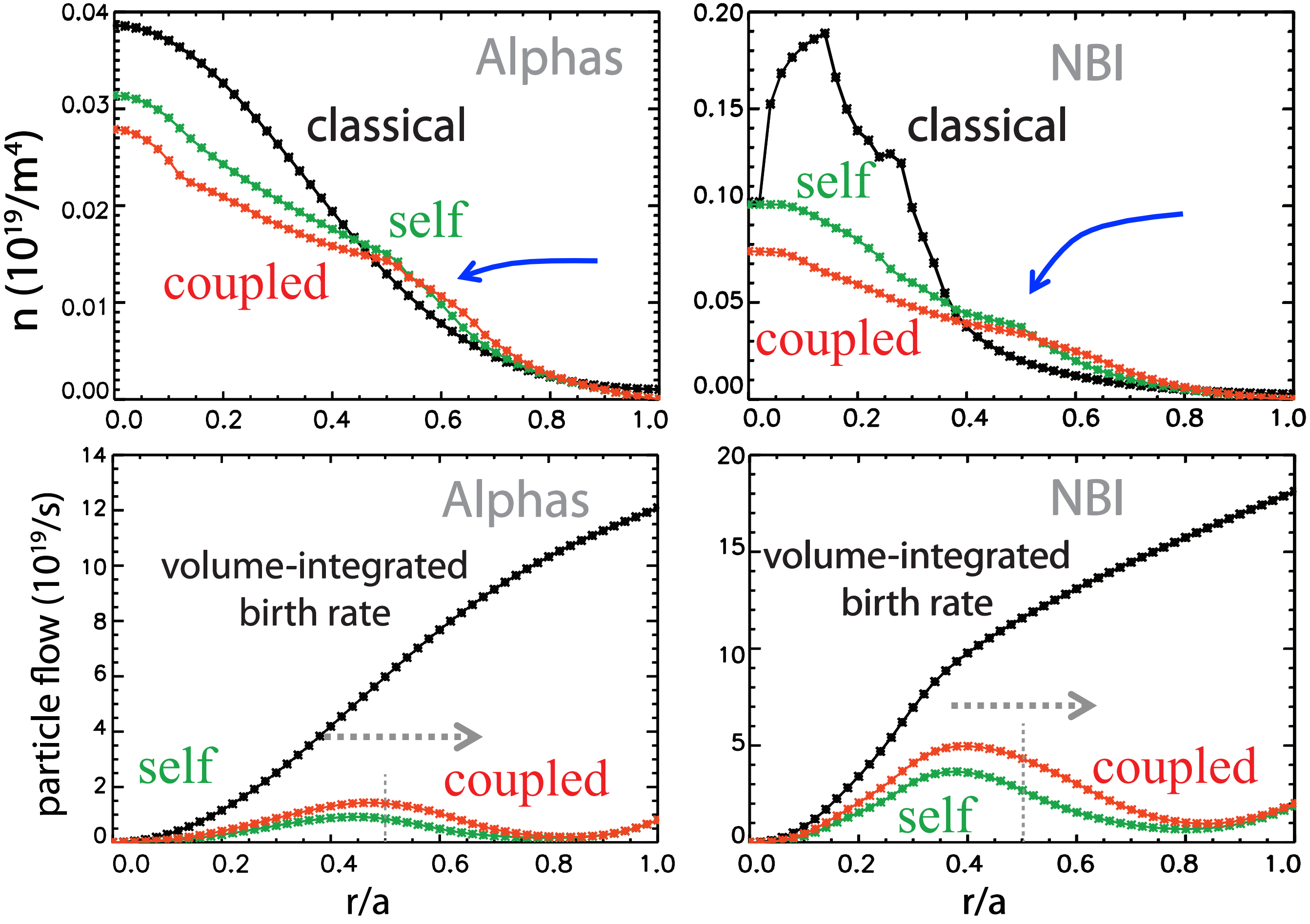
I. Introduction: Energetic Particle (EP) transport by Alfvén eigenmodes (AEs) and the need for reduced models

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

III. Predictions for ITER scenarios for burninig 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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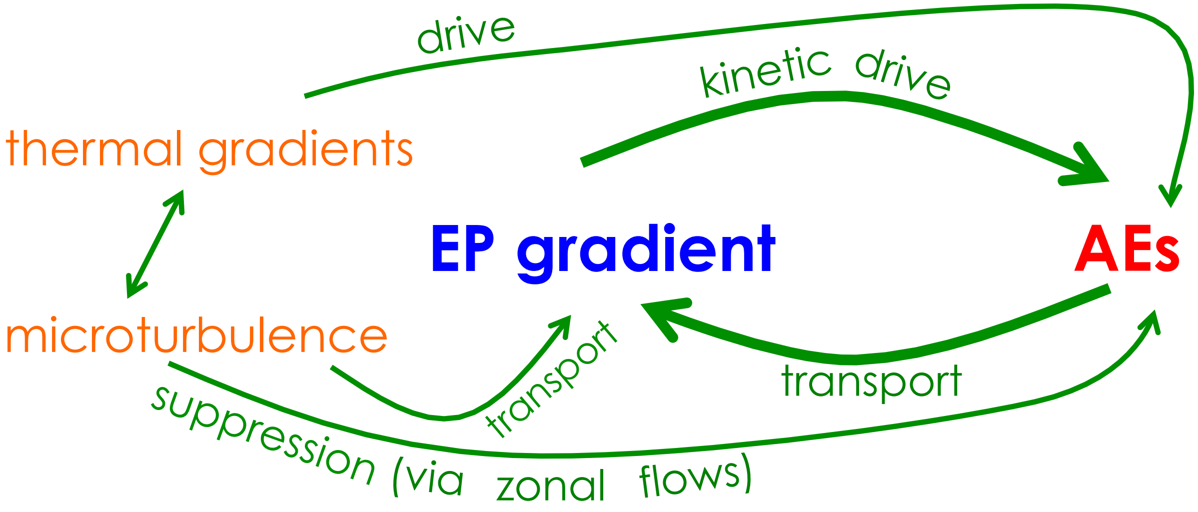
# EP transport by so-called “Alfvén eigenmodes” (AEs) can be very complicated

A quick primer on EP-transport jargon:

EPs: **Energetic particles** (fast ions). Fusion-sourced alpha particles or neutral beam injection (NBI) ions (deuterium).

AEs: **Alfvén eigenmodes**. Alfvén frequency MHD modes. EP kinetic drive and transport. Different flavors (RSAE, TAE, BAE, BAAE, EPM, etc.), don’t matter here.



drive

kinetic drive

thermal gradients

**EP gradient**

**AEs**

microturbulence

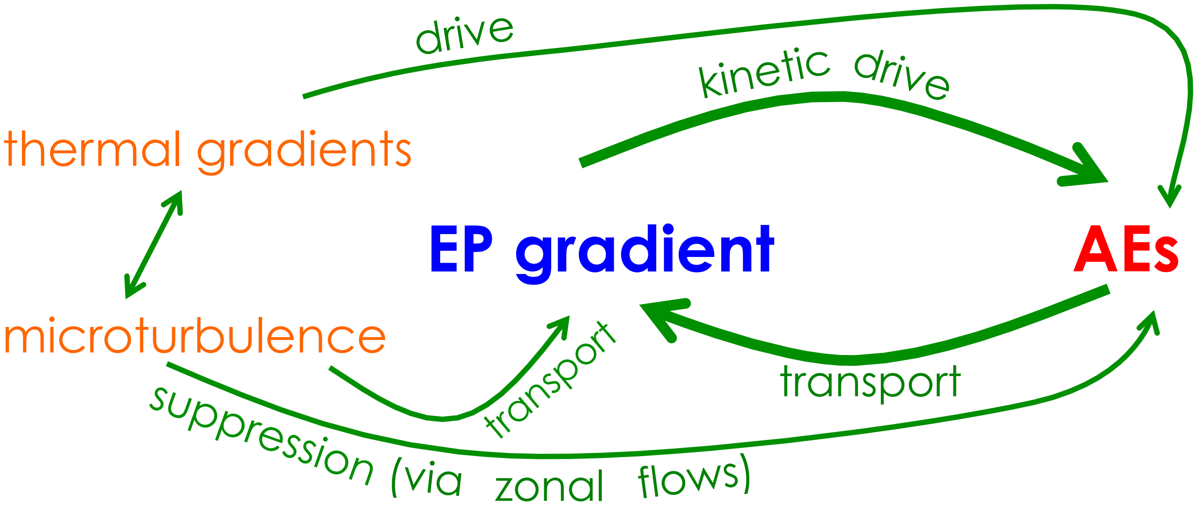
transport

transport

suppression (via zonal flows)

AEs drive most EP transport, mainly in the particle channel (i.e. transport is convective).

# EP transport by so-called "Alfvén eigenmodes" (AEs) can be very complicated



AEs drive most EP transport, mainly in the particle channel (i.e. transport is convective).

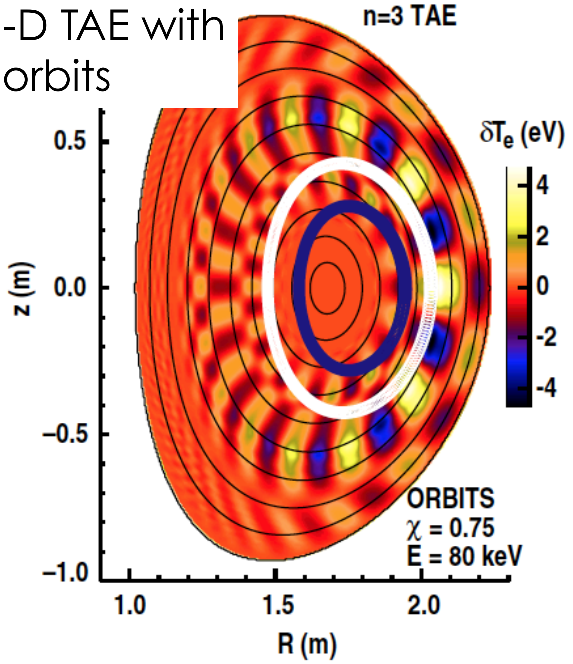
**EPs have large orbits relative to thermal species, leading to:**

### Sparse spectrum and high coherency:

- Intermittent transport, depending on global resonance intersections
- Saturation sensitive to stochastic processes (e.g., collisions, microturbulence)
- Formation of BGK bucket modes (frequency chirping)

### Transport non-locality

DIII-D TAE with EP orbits



# EP transport by so-called “Alfvén eigenmodes” (AEs) can be very complicated

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

When unstable, AEs drive the vast majority of EP transport, mainly in the particle channel (i.e. convective).

# It’s complicated!

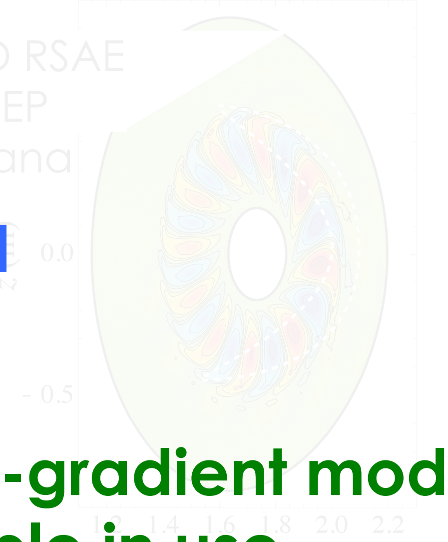
EPs have large orbits relative to thermal species, leading to:

Sparse spectrum and high coherency:

- Intermittent transport, depending on global resonance intersections
- Saturation sensitive to stochastic processes (e.g., collisions, microturbulence)
- Formation of BGK bucket modes (frequency chirping)

Transport non-locality

DIII-D RSAE with EP banana



**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[1]

## ALPHA transport EP continuity equation

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

fusion or beam source

slowing-down sink (plasma heating)

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

$$S = n_{\mathrm{D}} n_{\mathrm{T}} \langle \sigma \mathrm{v} \rangle_{\mathrm{DT}}$$

fusion source

$$n_{SD} = \int_0^\infty \frac{S\tau_s}{2} \frac{\Theta(\mathrm{E}_\alpha - \mathrm{E})}{\mathrm{E}_c^{3/2} + \mathrm{E}^{3/2}} \mathrm{E}^{1/2} d\mathrm{E}$$

Gaffey 1976

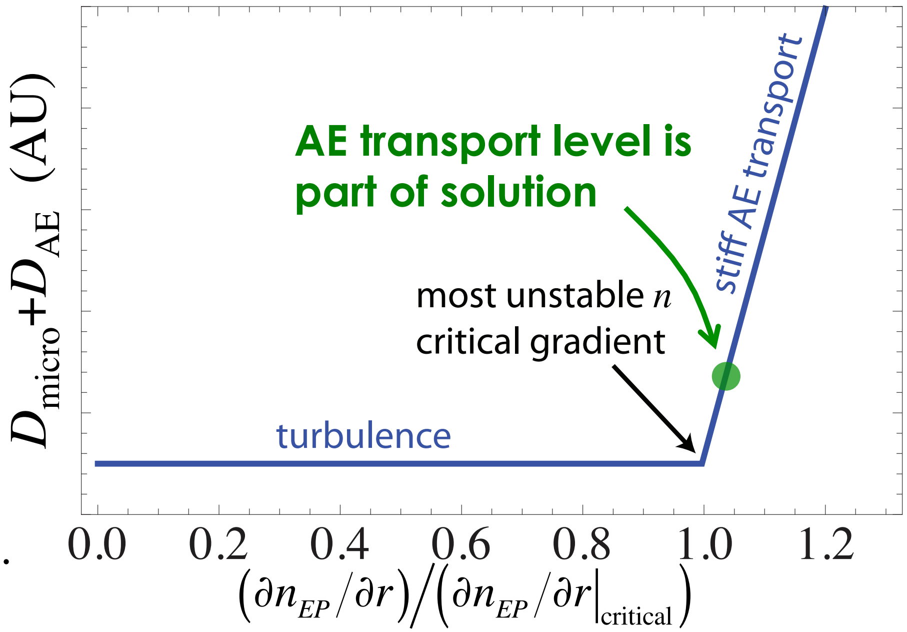
classical slowing-down density

**Diffusive EP flux:**

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

$D_{\mathrm{micro}}$ is the effective background diffusion coefficient from the Angioni quasilinear model[2] fit to GYRO.

**Critical gradient** as a function of $r$ determined by TGLFEP, the **crucial input**.



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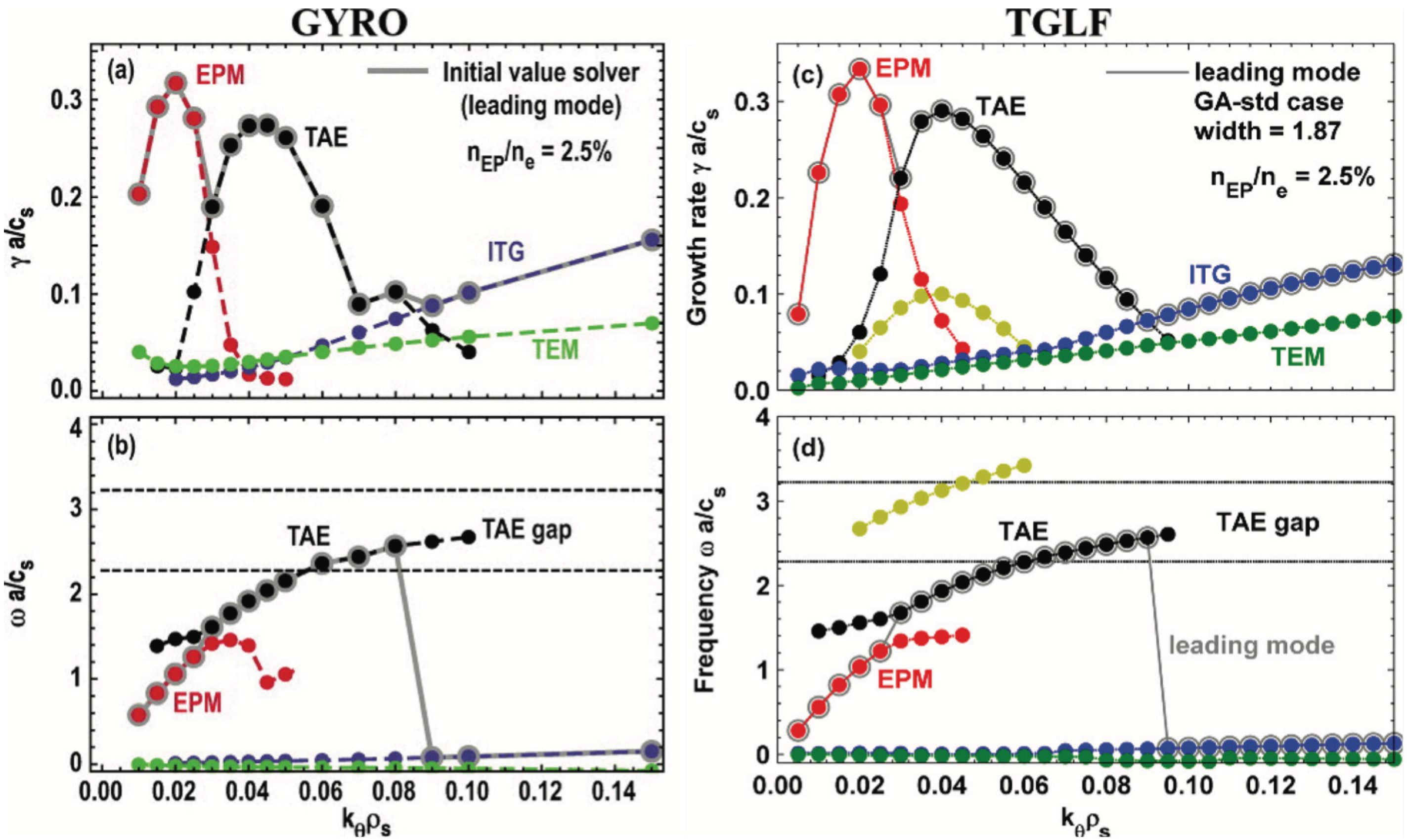
[1] E.M. Bass and R.E. Waltz, PoP **17** 112319 (2010)

[2] Angioni and Peters, PoP **15** 052307 (2008)

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

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



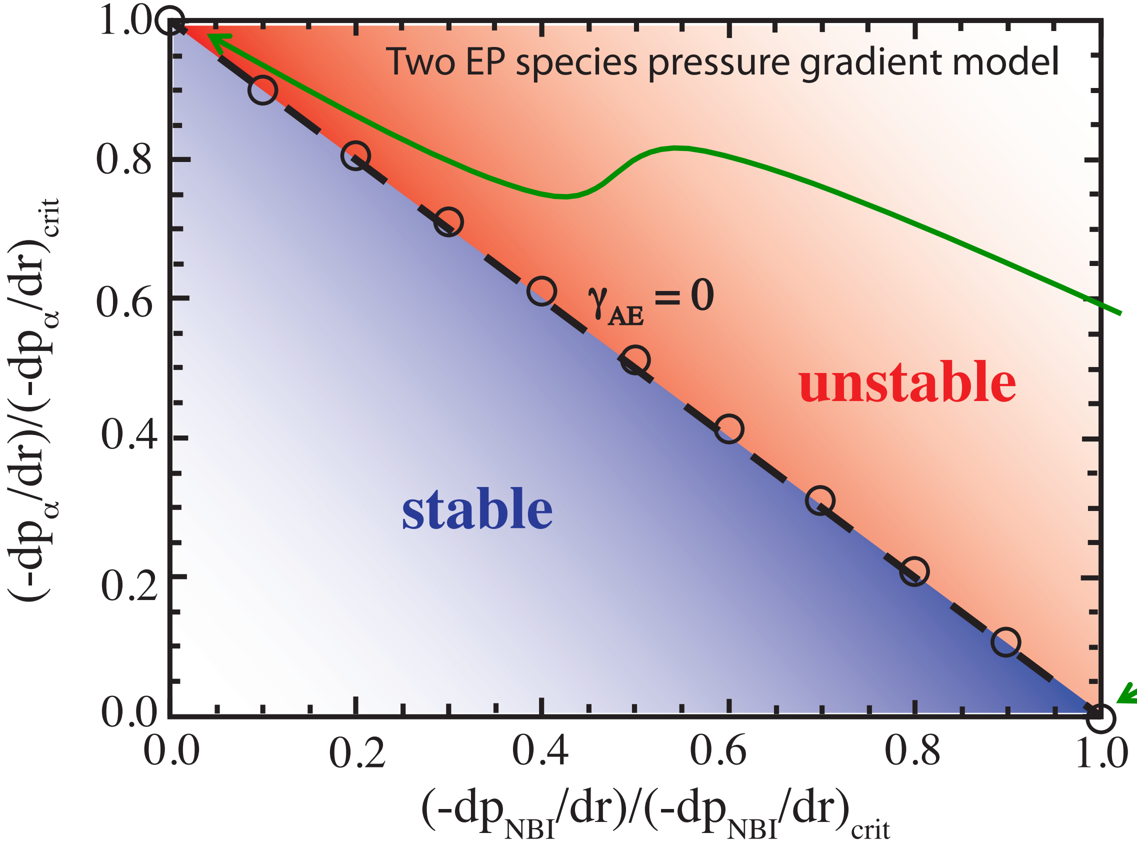
**TGLFEP**[1]**:** A parallelized wrapper that searches across mode number and drive strength for the critical gradient.

[1] He Sheng, R.E. Waltz, and G.M. Staebler, PoP **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.

$$\sum_i \frac{dp_i / dr}{(dp_i / dr)_{crit}} \geq 1$$



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

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

[1] He Sheng, R.E. Waltz, and G.M. Staebler, PoP **24**, 072305 (2017)

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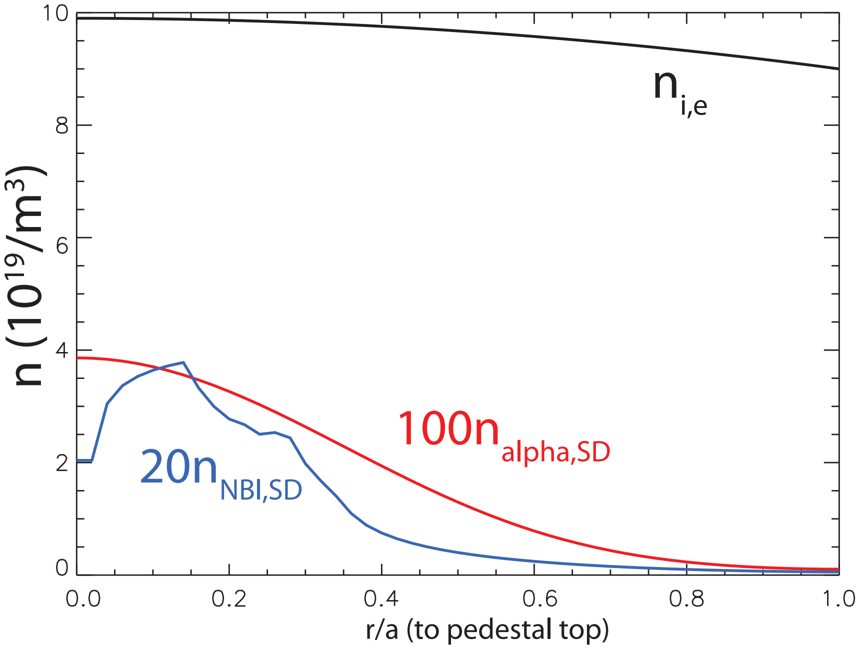
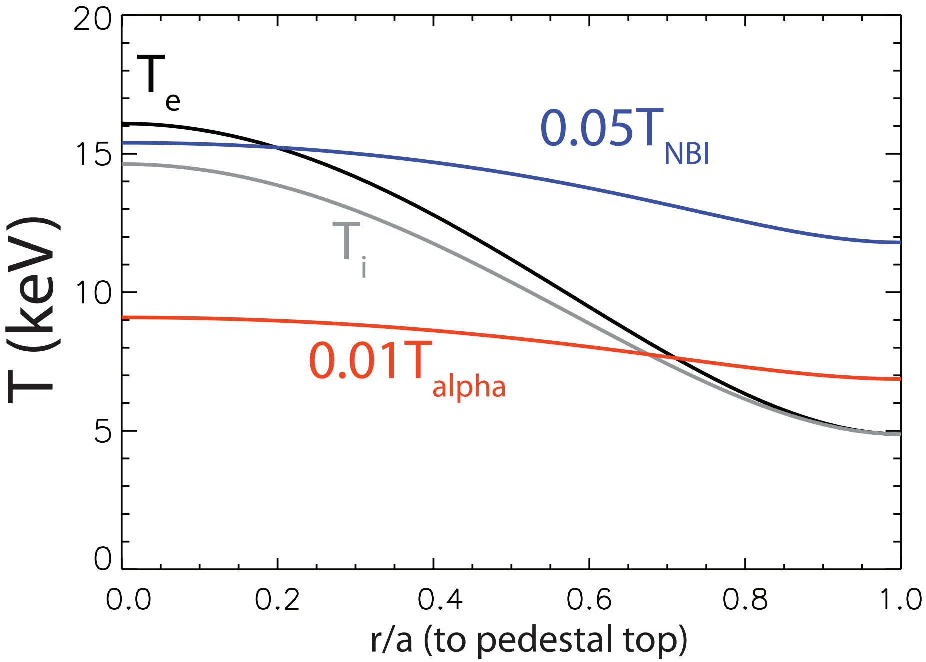
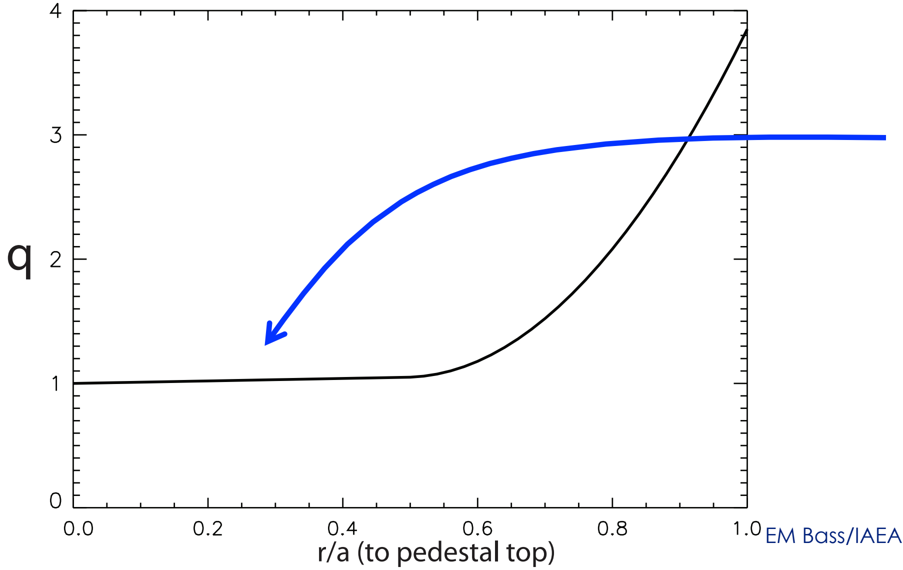
# We consider a 30 MW Q≈10 ITER profile prediction based on EPED1 and tGYRO TGLF core transport[1]



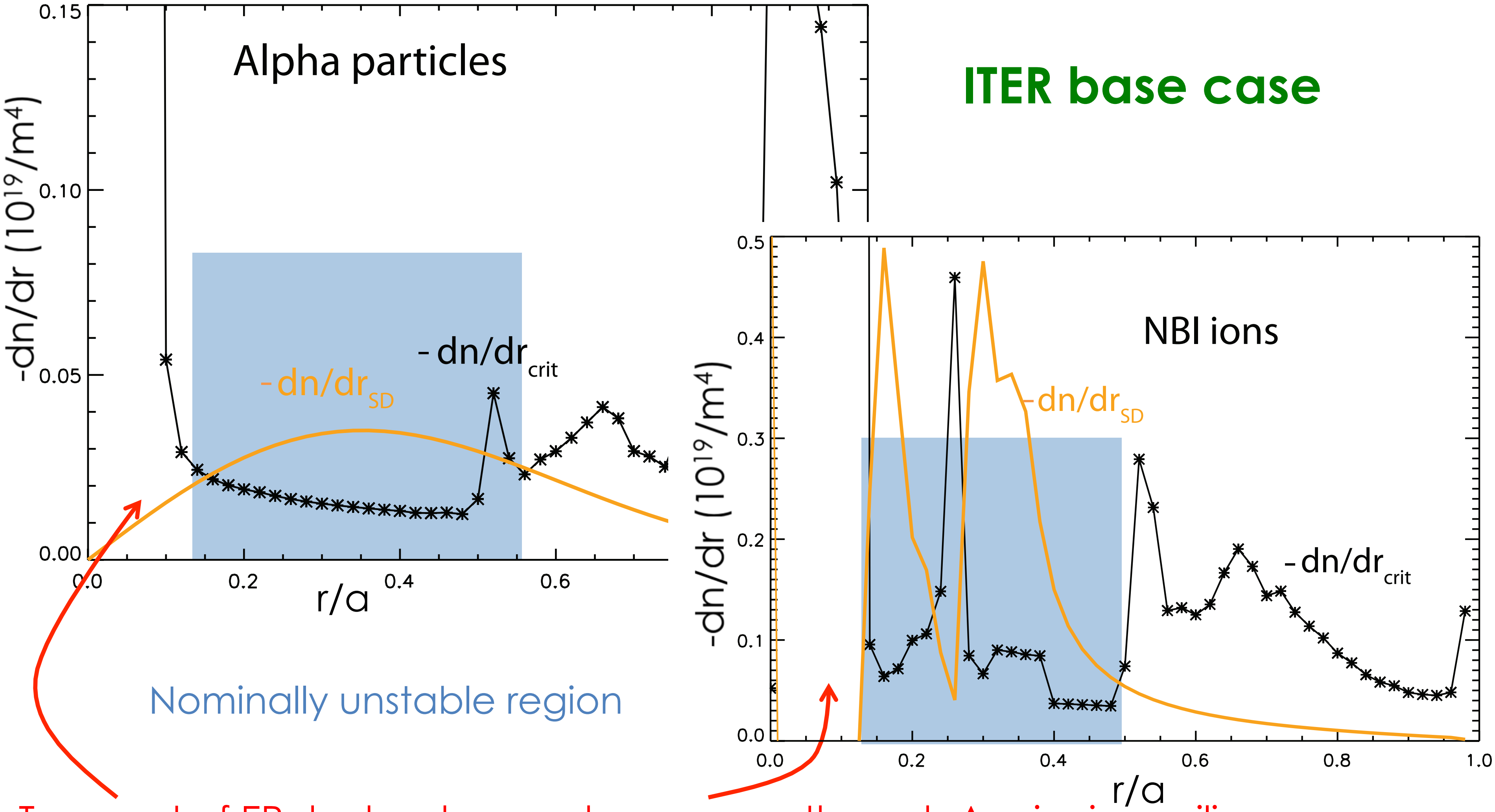




Very weak central shear region proves to be the most AE unstable for the base case scenario with **maximum current drive and current penetration**.

[1] J. Kinsey, G.M. Staebler, J. Candy, R.E. Waltz, and R. Budny, Nucl. Fusion **51**, 083001 (2011)

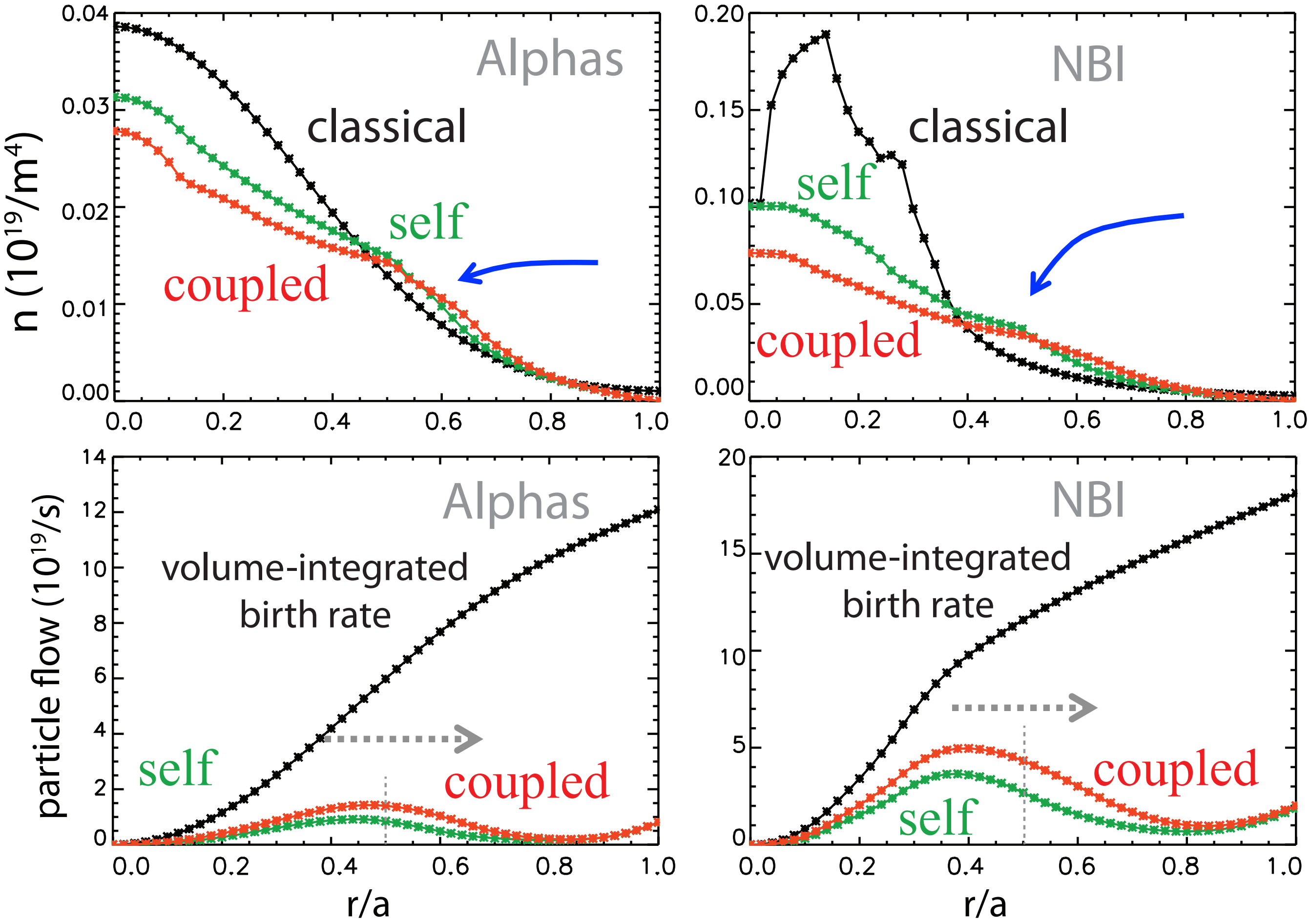
# As in 2015 GYRO ITER simulations[1], TGLFEP finds unstable AEs only in the mid core where $-dn/dr_{SD} > -dn/dr_{crit}$



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

[1] R.E. Waltz, E.M. Bass, W.W. Heidbrink, and M.A. VanZeeland, Nucl. Fusion **55**, 123012 (2011)

# 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.

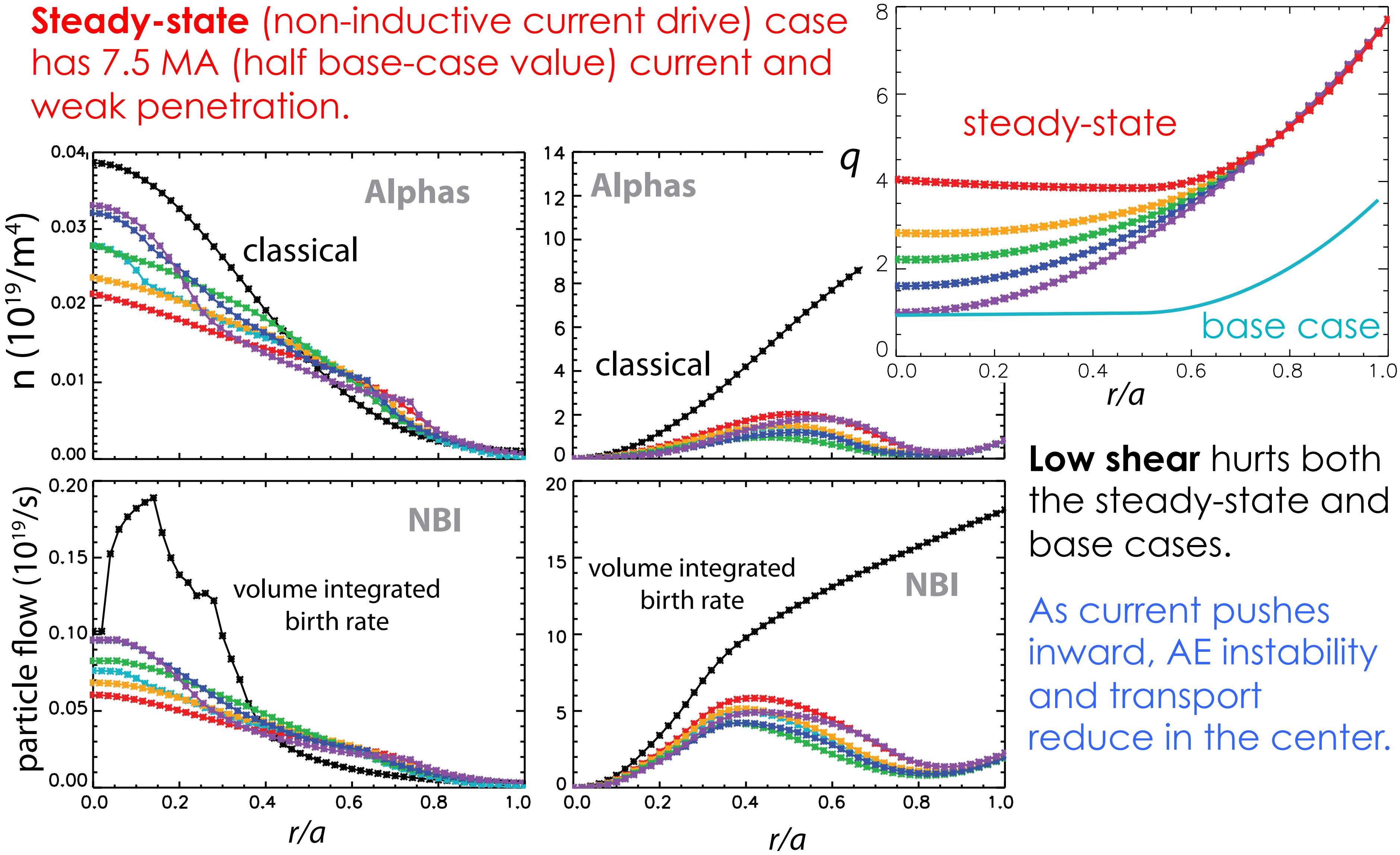
EPs redistributed from **inner core to outer core**

| | alphas | NBI ions |
|---|---|---|
| self: | 14.1% | 23.1% |
| coupled: | 23.5% | 37.3% |

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

# 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.



**Low shear** hurts both the steady-state and base cases.

As current pushes inward, AE instability and transport reduce in the center.

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# Summary:
# TGLFEP+ALPHA reduced model code ITER predictions

- The TGLFEP+ALPHA reduced model robustly predicts **EP redistribution from the mid core to the outer core**, but with minimal net edge loss.

- Reductions in ITER current (increased $q$) or current penetration (increased $q_{min}$ 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**.

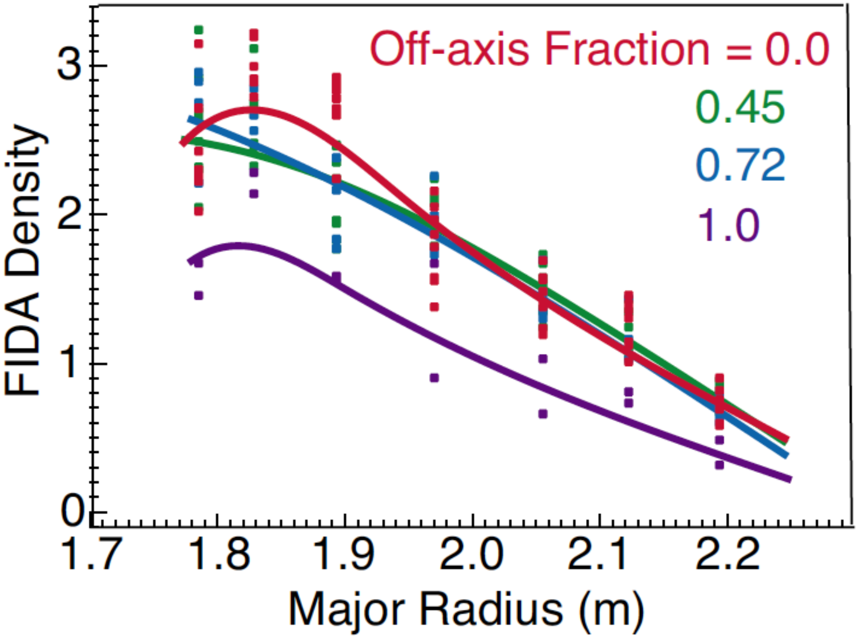
Going forward:

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

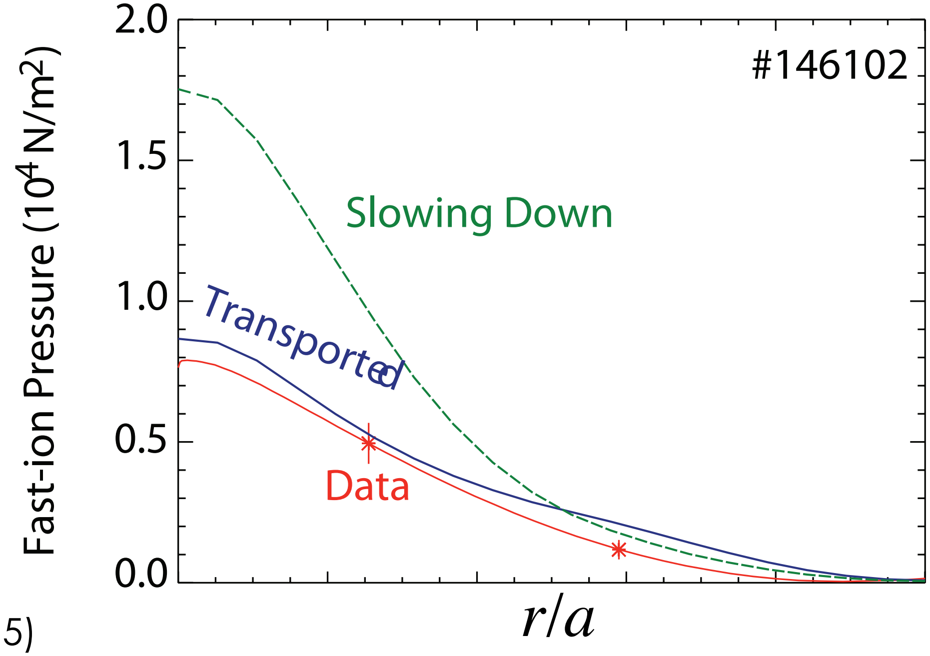
- Deploy **TGLFEP+ALPHA model into the AToM2** whole-device modeling project for use by broader community

- Adjust inputs considering **broadened heating and current deposition profiles** in an integrated modeling feedback loop

# 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)

[2] E.M. Bass and R.E. Waltz, Phys. Plasmas **24**, 122302 (2017)

# 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].

$\gamma_{\text{AE-ITG/TEM}}$

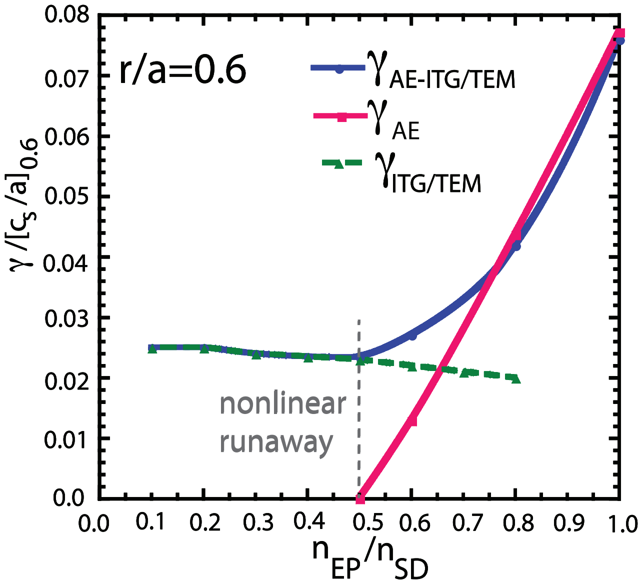
EP+thermal drive on AEs

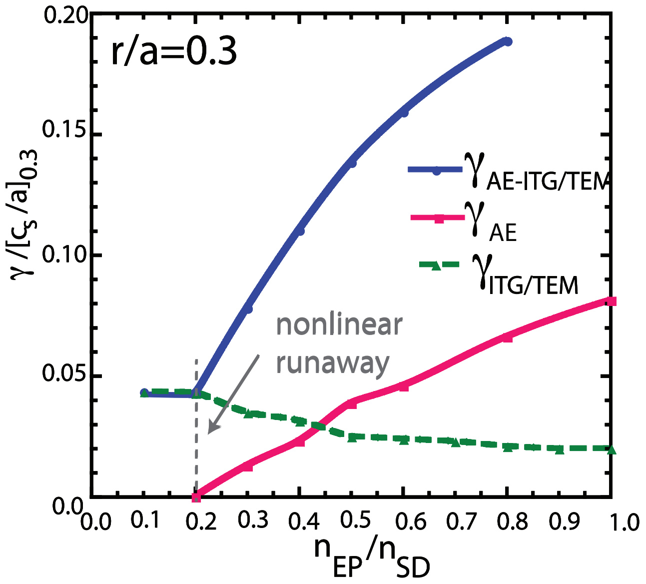
$\gamma_{\text{AE}}$

only EP drive on AEs

$\gamma_{\text{ITG/TEM}}$

leading microturbulent growth rate



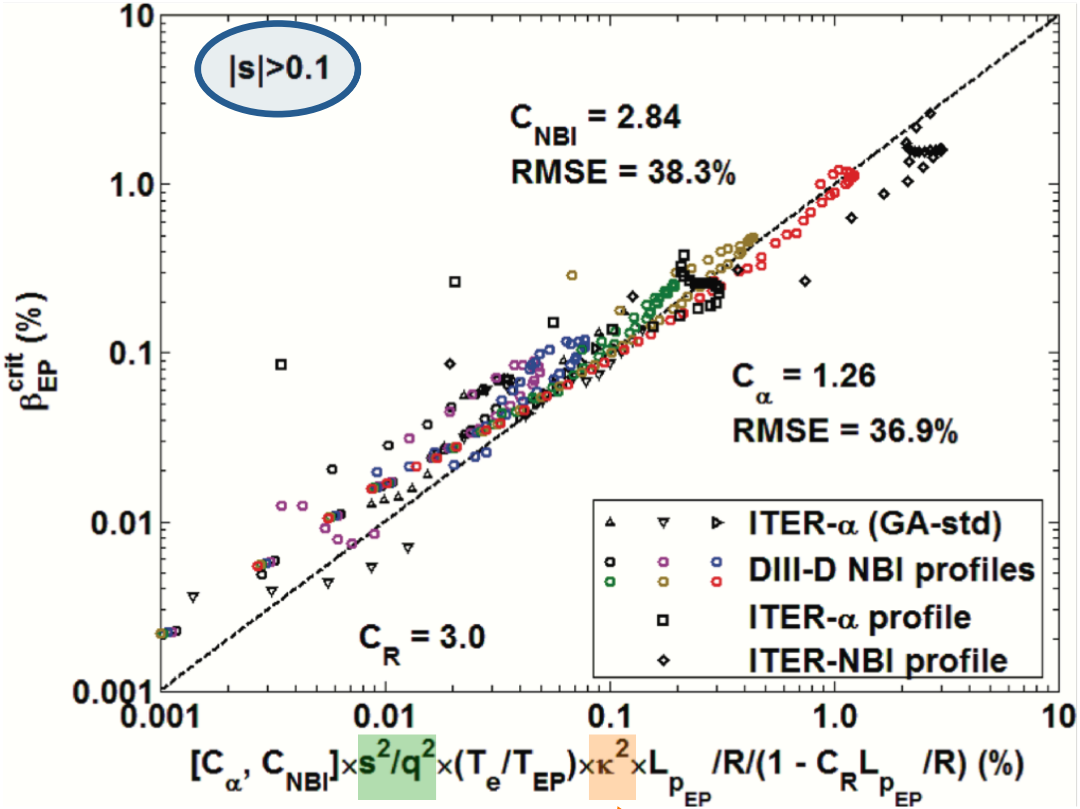


Runaway onset at $\gamma_{\text{AE+ITG/TEM}}=\gamma_{\text{ITG/TEM}}$ is due to suppression of AEs by microturbulence-driven zonal flows.

By luck, the **much simpler condition $\gamma_{\text{AE}}$=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[1].

*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.**

[1] He Sheng et al., PoP **24**, 072305 (2017)