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

E.M. Bass[1] and R.E. Waltz[2]

[1]UC San Diego
[2]General Atomics

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

Presented at
2018 IAEA Fusion Energy Conference
Ahmedabad, Gujarat, India

October 22 – 27, 2018

Supported by US DOE GSEP-SciDAC
Computations performed at NERSC

UCSD

Outline

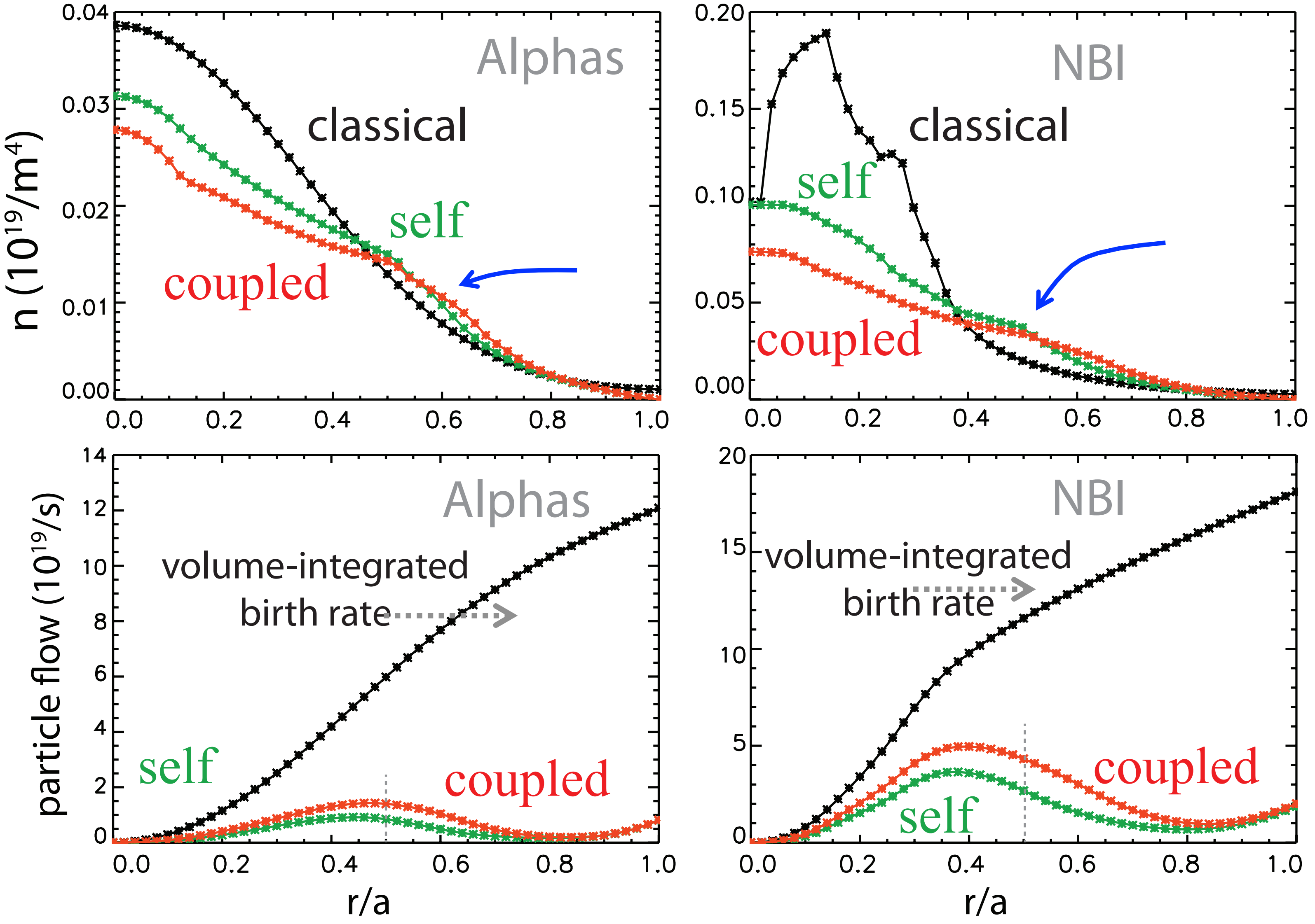
I. Introduction: Energetic Particle (EP) transport by Alfvén eigenmodes (AEs) and the need for reduced models

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.

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

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

A quick primer on EP-transport jargon:

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).

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

A quick primer on EP-transport jargon:

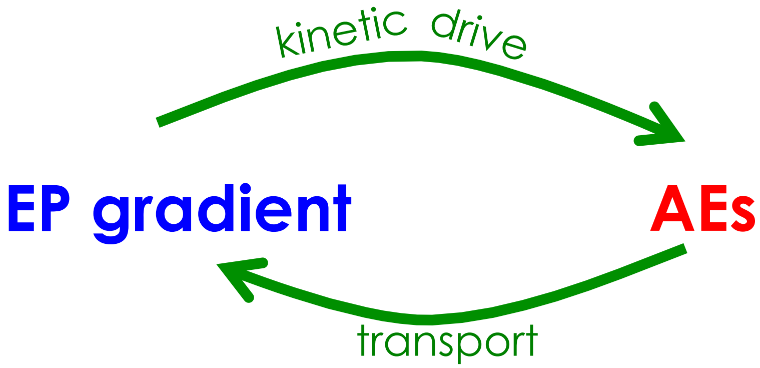
EPs:	**Energetic particles** (fast ions). Fusion-sourced alpha particles or neutral beam injection (NBI) ions (deuterium).
AEs:	**Alfvén eigenmodes**. Alfvén frequency MHD modes. EP kinetic drive and transport. Different flavors (RSAE, TAE, BAE, BAAE, EPM, etc.), don't matter here.

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.



kinetic drive

EP gradient

AEs

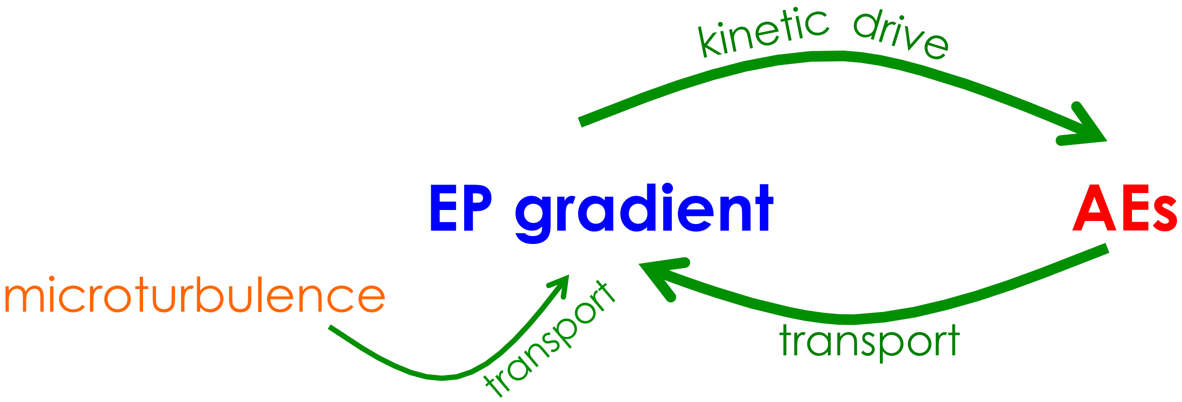
transport

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.

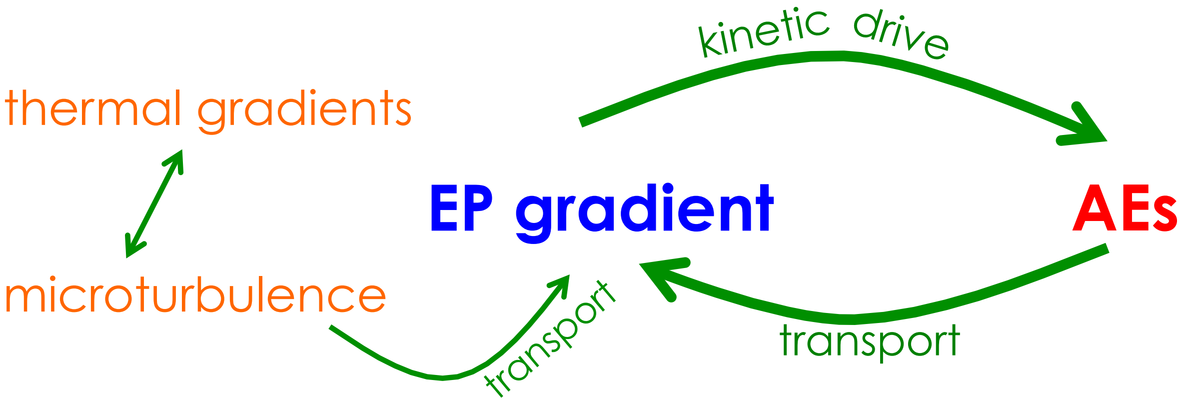


EP transport by so-called "Alfvén eigenmodes" (AEs) can be very complicated

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.



kinetic drive

thermal gradients

EP gradient

AEs

microturbulence

transport

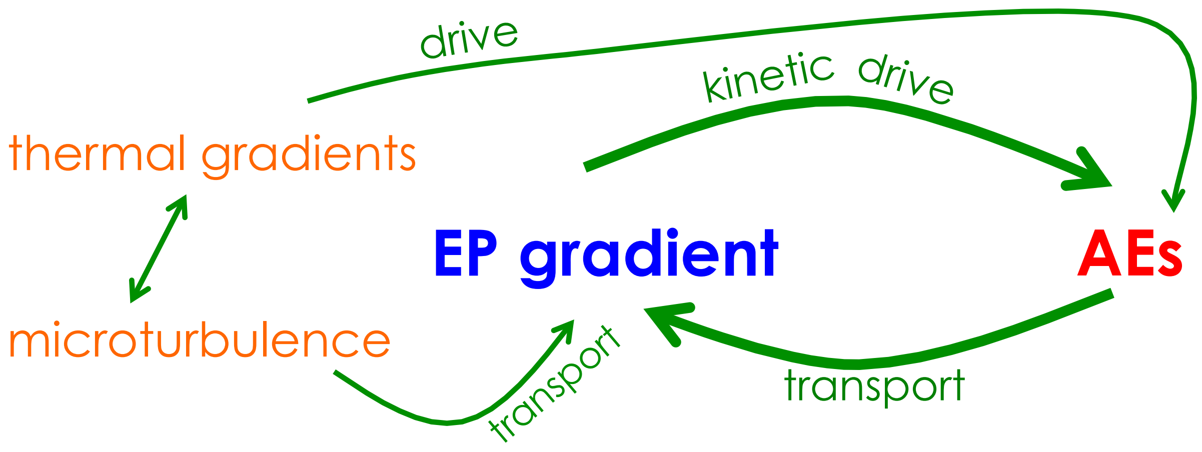
transport

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.

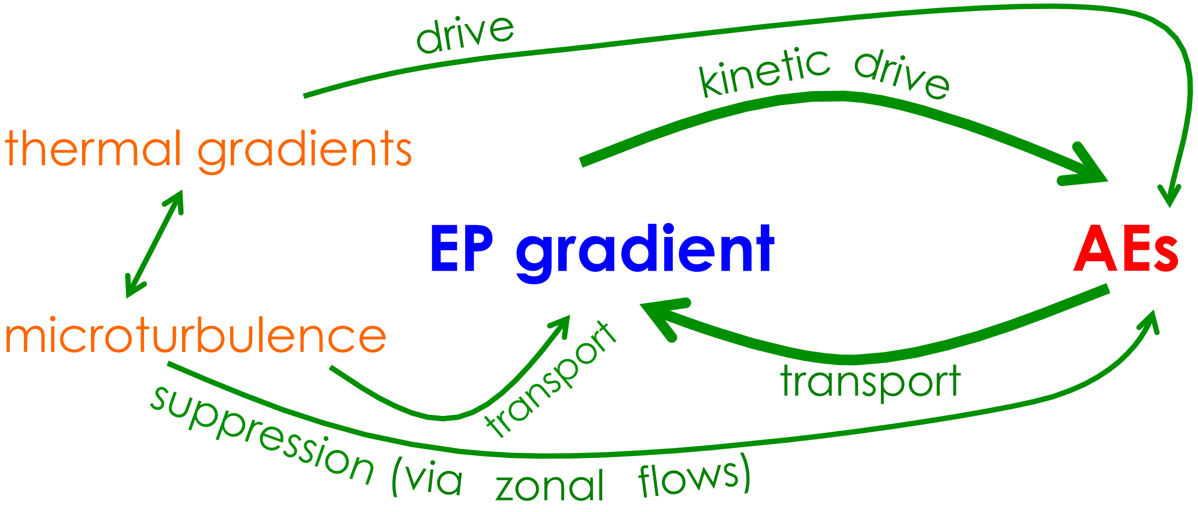


EP transport by so-called "Alfvén eigenmodes" (AEs) can be very complicated

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.

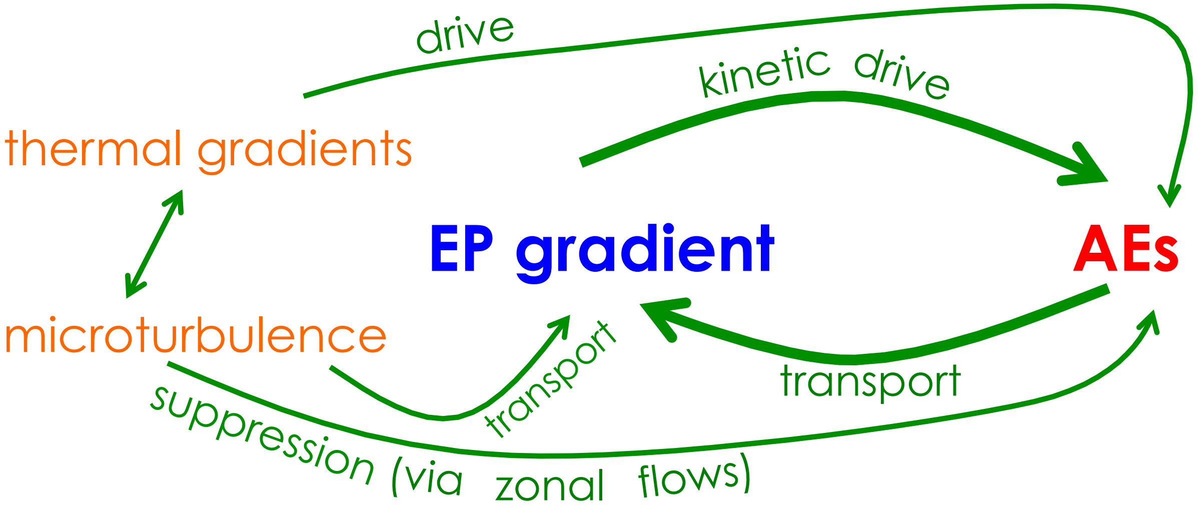


EP transport by so-called "Alfvén eigenmodes" (AEs) can be very complicated

A quick primer on EP-transport jargon:

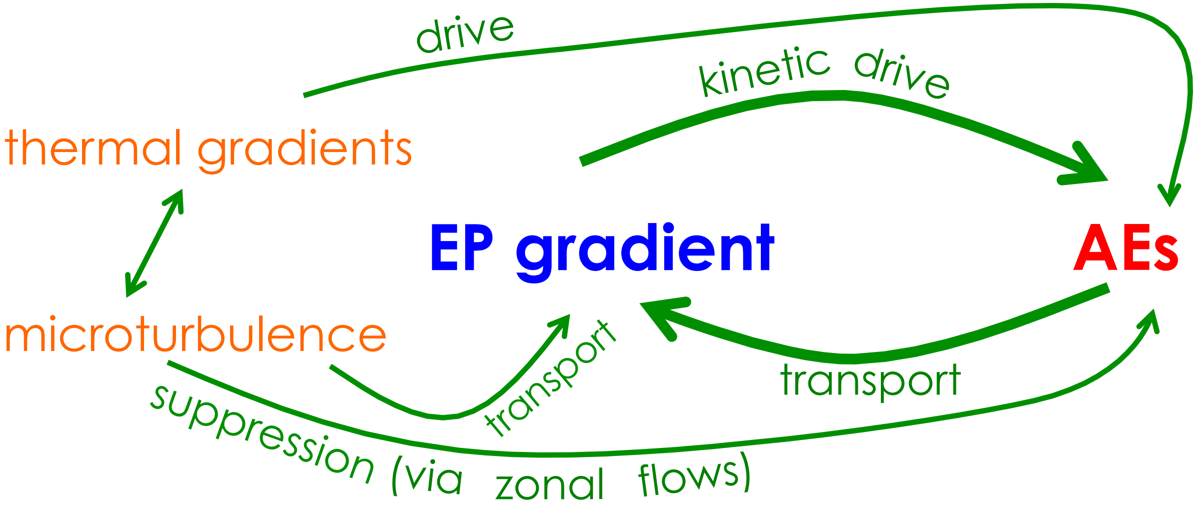
EPs: **Energetic particles** (fast ions). Fusion-sourced alpha particles or neutral beam injection (NBI) ions (deuterium).

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



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



drive

kinetic drive

thermal gradients

EP gradient

AEs

microturbulence

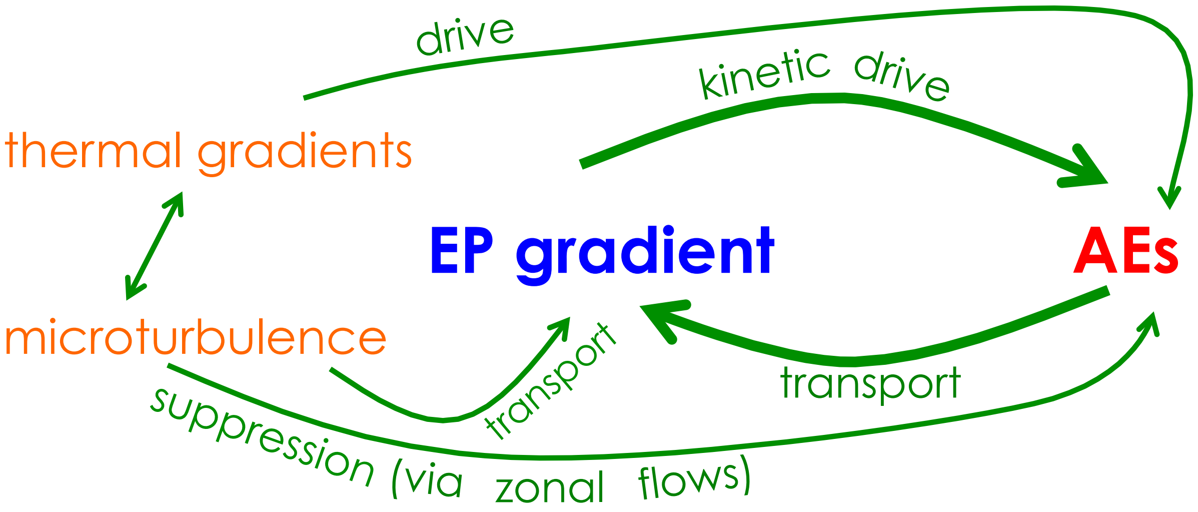
transport

transport

suppression (via zonal flows)

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

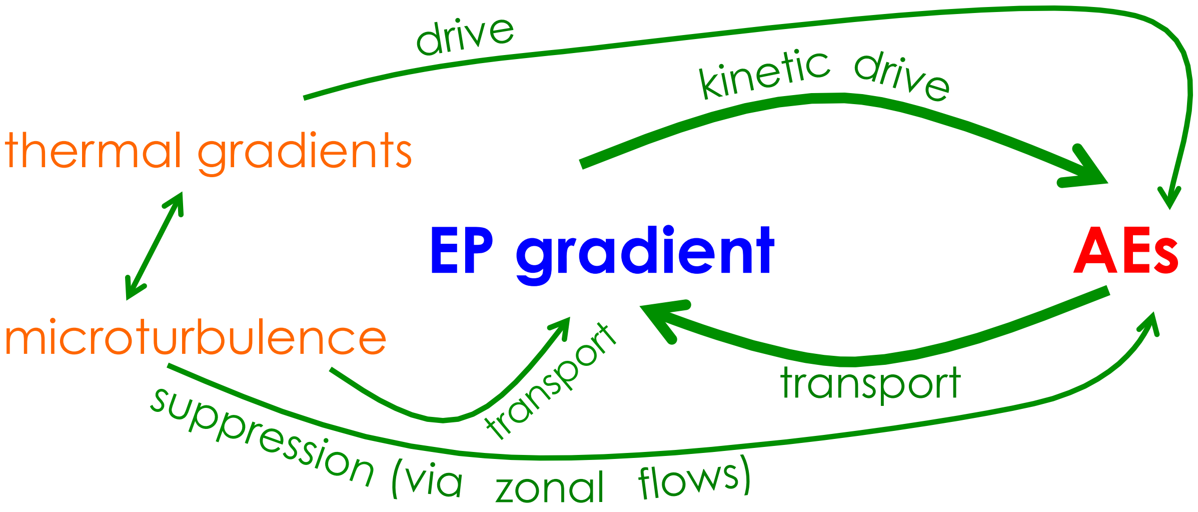
EP transport by so-called "Alfvén eigenmodes" (AEs) can be very complicated



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:

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



drive

kinetic drive

thermal gradients

EP gradient

AEs

microturbulence

transport

transport

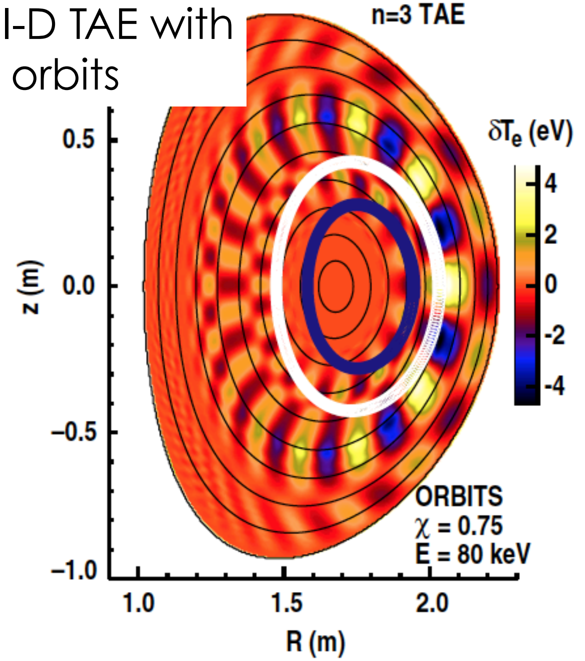
suppression (via zonal flows)

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

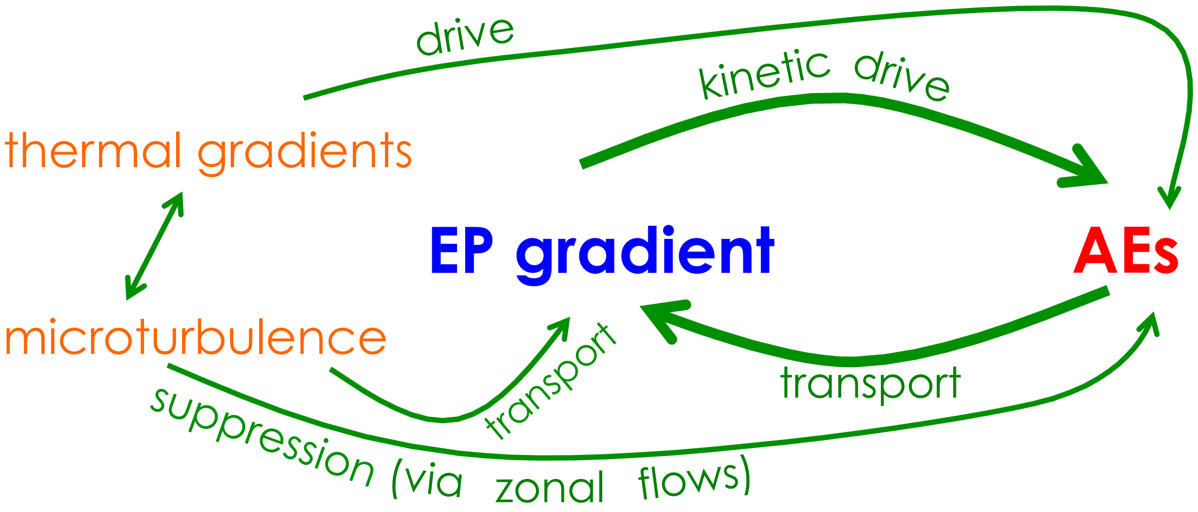
EPs have large orbits relative to thermal species, leading to:

Transport non-locality

DIII-D TAE with EP orbits



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



drive

kinetic drive

thermal gradients

EP gradient

AEs

microturbulence

transport

transport

suppression (via zonal flows)

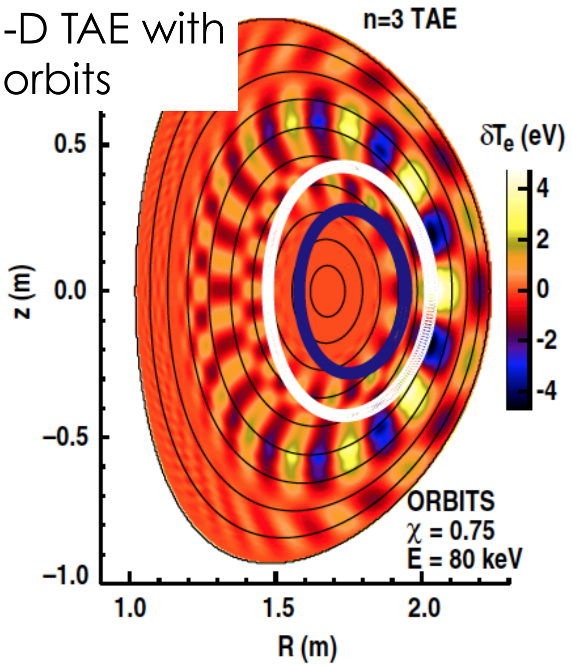
AEs drive most EP transport, mainly in the particle channel (i.e. transport is convective).

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

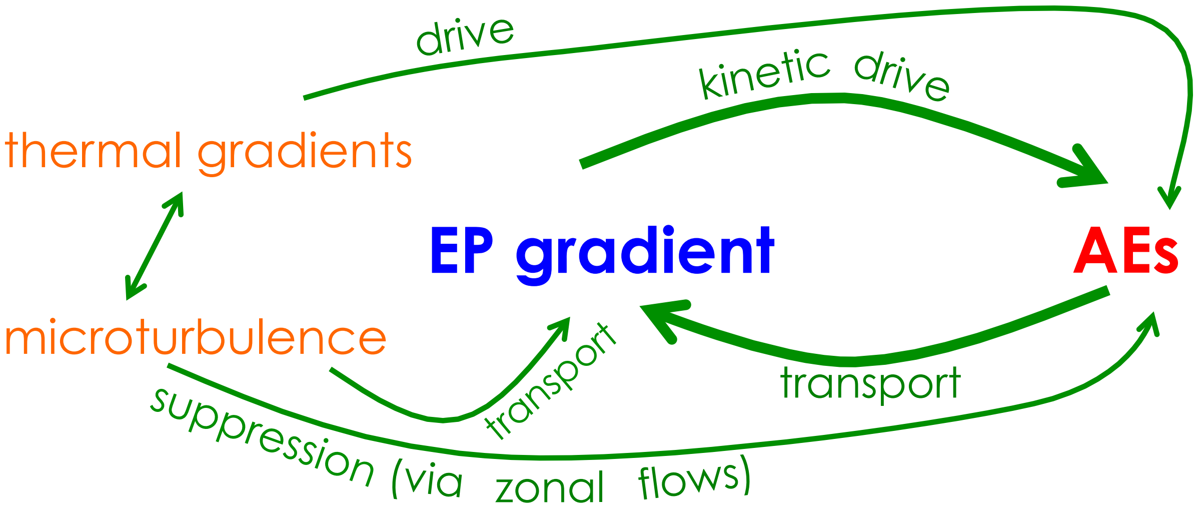
Sparse spectrum and high coherency:

Transport non-locality

DIII-D TAE with EP orbits



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).

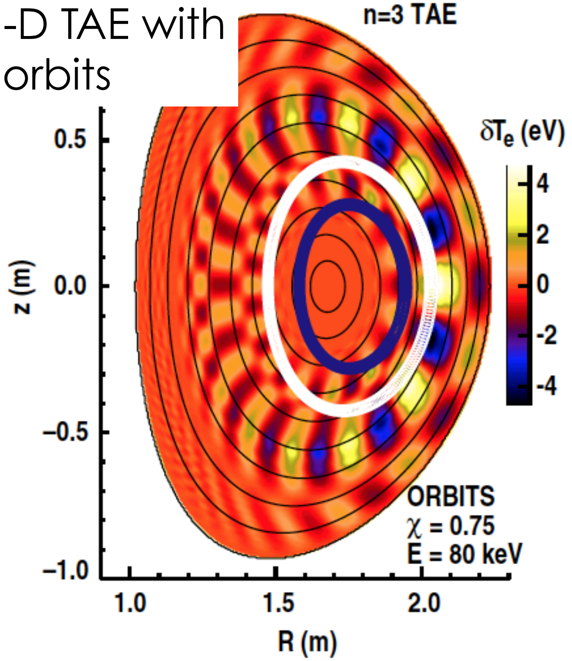
EPs have large orbits relative to thermal species, leading to:

Sparse spectrum and high coherency:

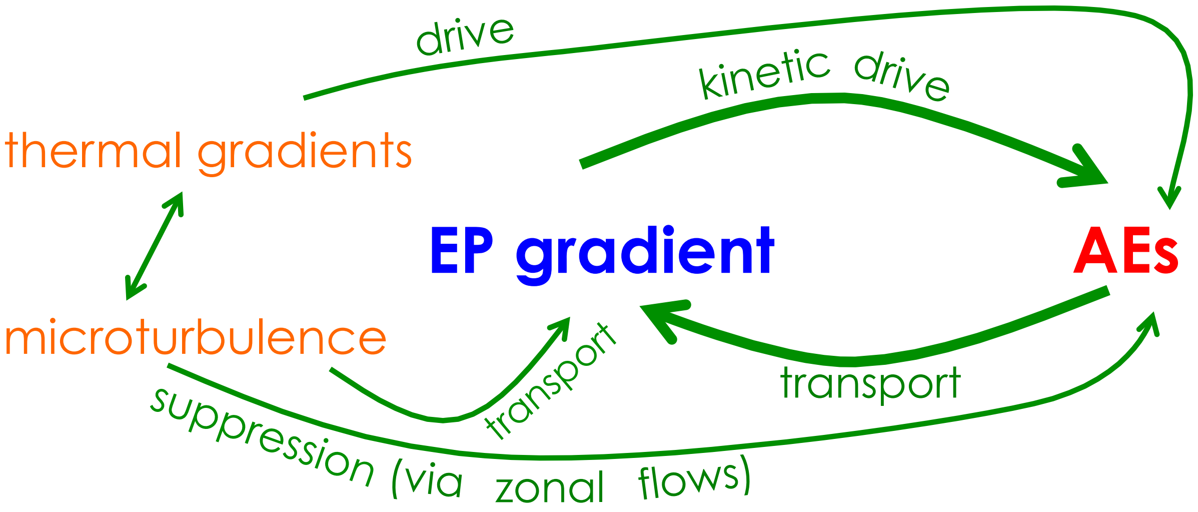
- Intermittent transport, depending on global resonance intersections

Transport non-locality

DIII-D TAE with EP orbits



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



drive

kinetic drive

thermal gradients

EP gradient

AEs

microturbulence

transport

transport

suppression (via zonal flows)

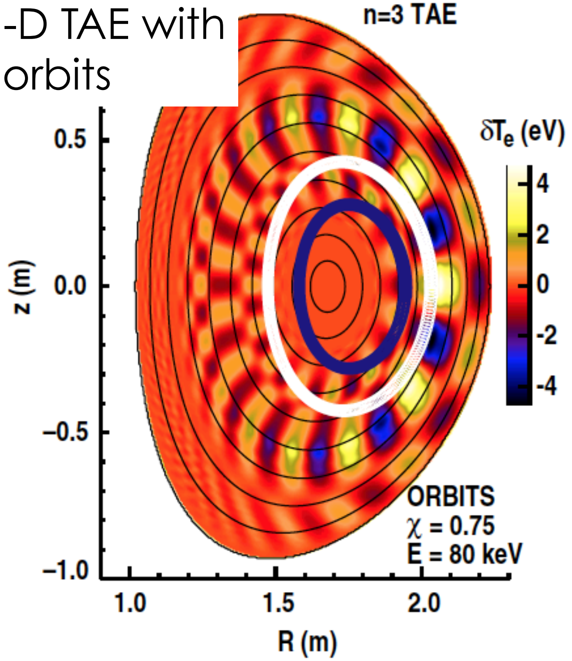
AEs drive most EP transport, mainly in the particle channel (i.e. transport is convective).

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

Sparse spectrum and high coherency:

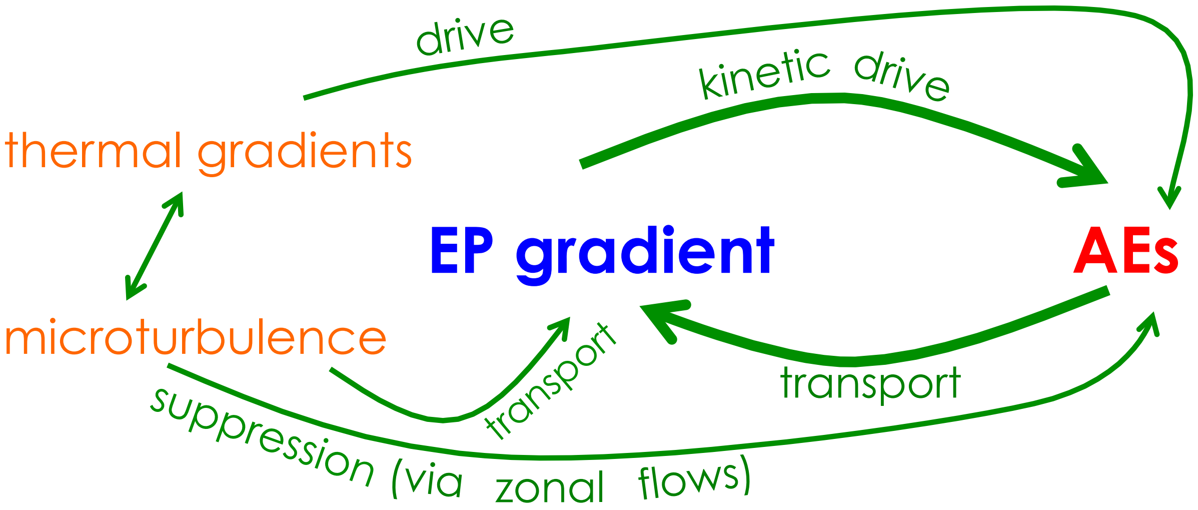
- Intermittent transport, depending on global resonance intersections
- Saturation sensitive to stochastic processes (e.g., collisions, microturbulence)

Transport non-locality



DIII-D TAE with EP orbits

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



drive

kinetic drive

thermal gradients

EP gradient

AEs

microturbulence

transport

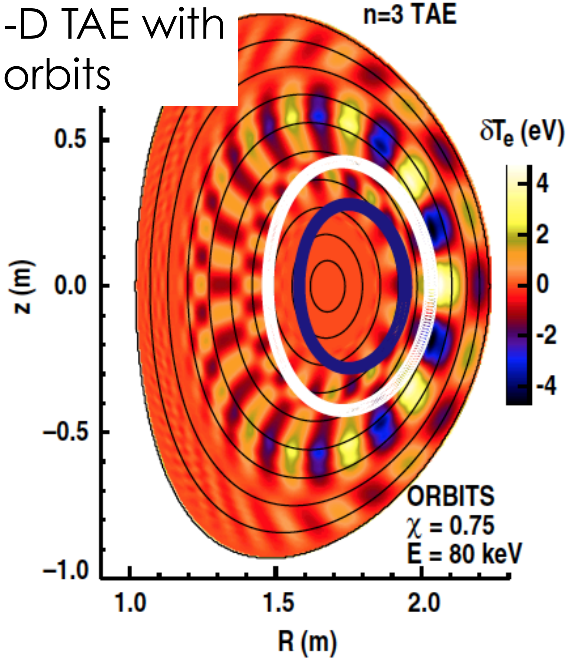
transport

suppression (via zonal flows)

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

Transport non-locality

DIII-D TAE with EP orbits



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)

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

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

mainly in the particle channel
(i.e. transport is convective).

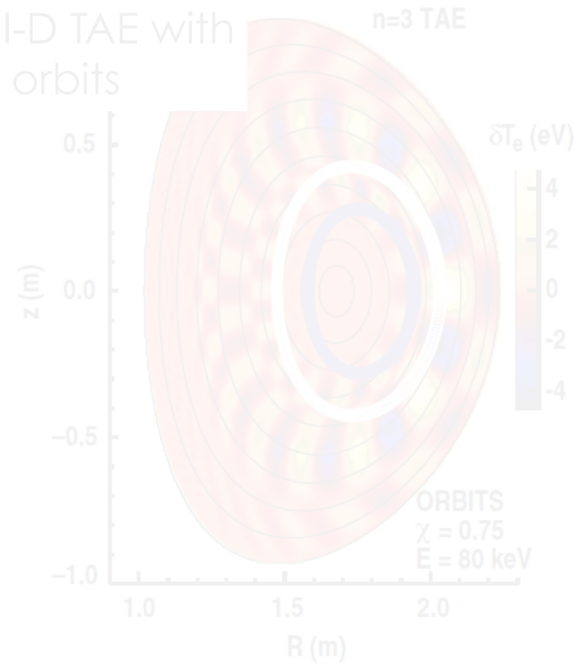
EPs have large orbits relative to thermal species, leading to:

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?

It’s complicated!

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.

AE transport … mainly in the particle channel (i.e. transport is convective).

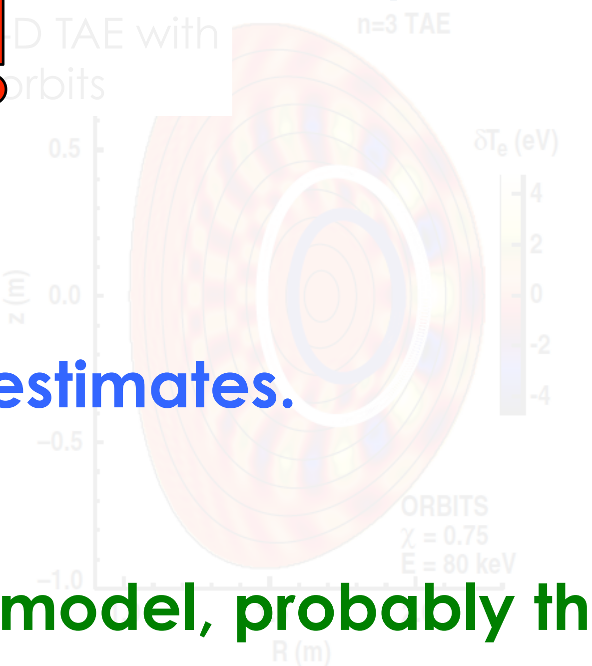
EPs have large orbits relative to thermal species, leading to:

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 orbits



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

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

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

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

[1] E.M. Bass and R.E. Waltz, PoP **17** 112319 (2010)
[2] Angioni and Peters, PoP **15** 052307 (2008)

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

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

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

---

[1] E.M. Bass and R.E. Waltz, PoP **17** 112319 (2010)
[2] Angioni and Peters, PoP **15** 052307 (2008)

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

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

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

fusion source

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

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

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)

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

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

fusion source

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

classical
slowing-down
density

Gaffey 1976

---

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

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

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)

Diffusive EP flux:

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

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

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

fusion source

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

classical
slowing-down
density

Gaffey 1976

---

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

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

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)

Diffusive EP flux:

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

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

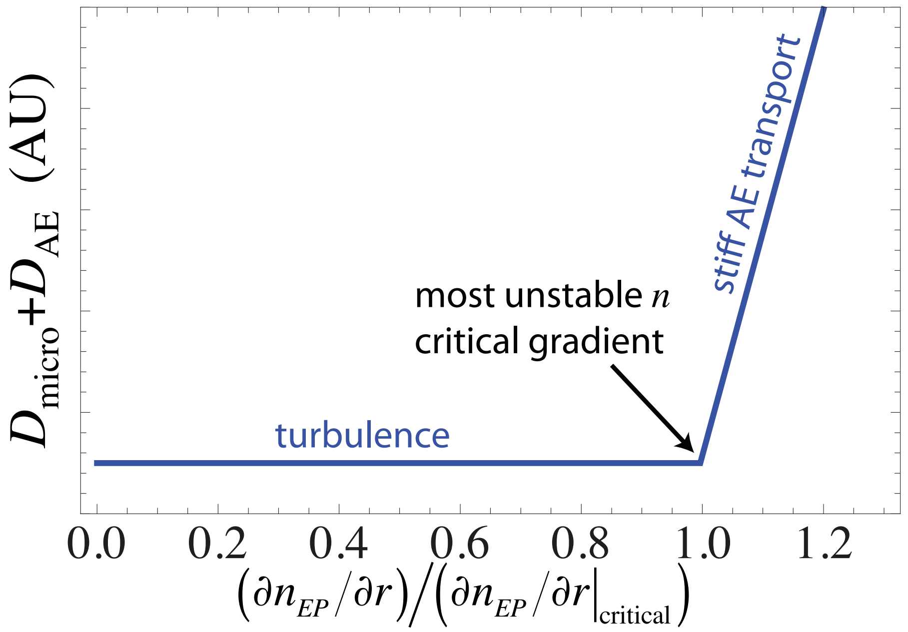
$$S = n_{\mathrm{D}} n_{\mathrm{T}}\langle\sigma \mathrm{v}\rangle_{\mathrm{DT}}$$

fusion source

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

classical slowing-down density

Gaffey 1976



---

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

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

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)

Diffusive EP flux:

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

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

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

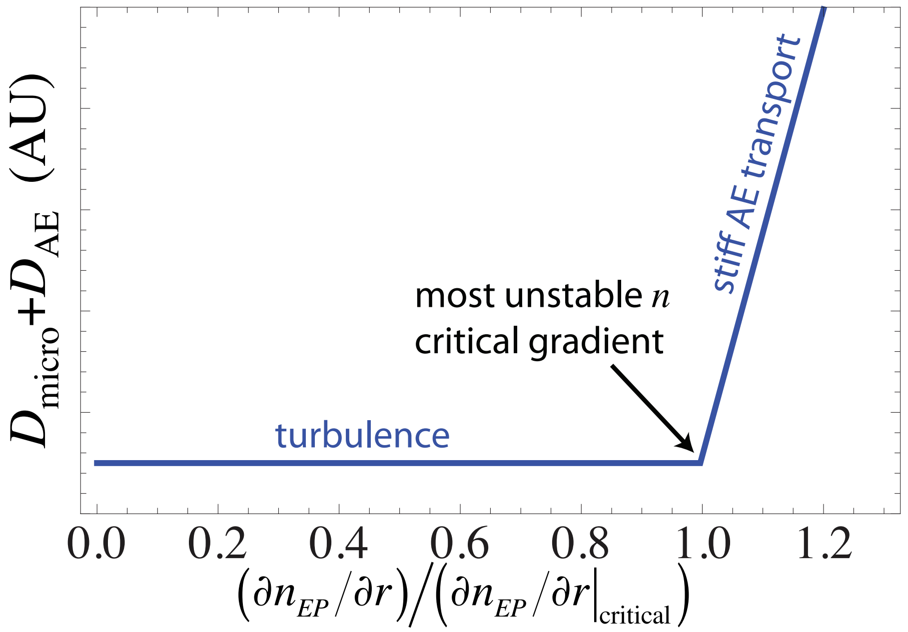
$$S = n_{\text{D}} n_{\text{T}} \left\langle \sigma \text{v} \right\rangle_{\text{DT}}$$

fusion source

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

classical
slowing-down
density

Gaffey 1976



---

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

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

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)

Diffusive EP flux:

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

D_{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**.

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

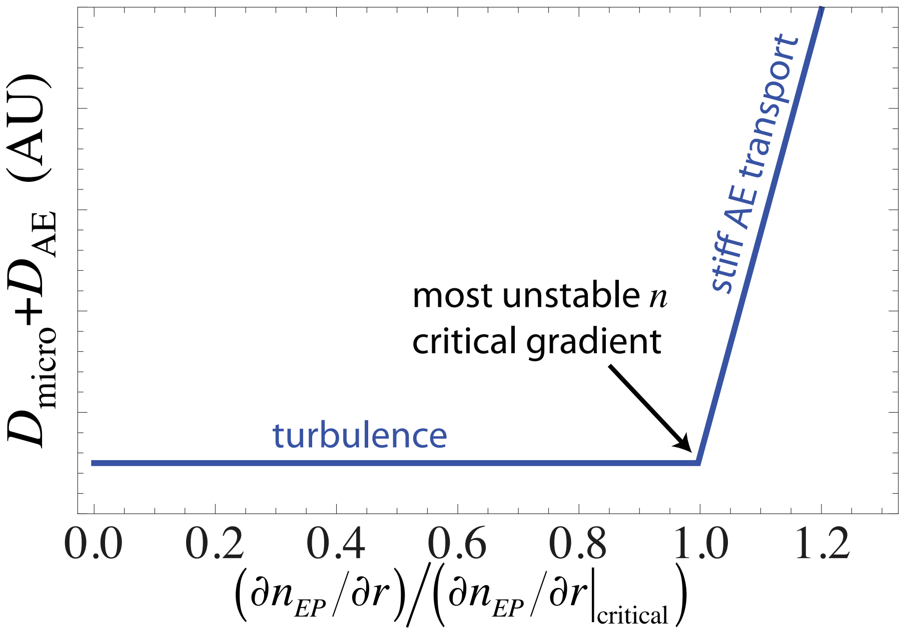
$$S = n_{\text{D}} n_{\text{T}} \left\langle \sigma \text{v} \right\rangle_{\text{DT}}$$

fusion source

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

classical
slowing-down
density

Gaffey 1976



---

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

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

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)

Diffusive EP flux:

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

D_{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**.

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

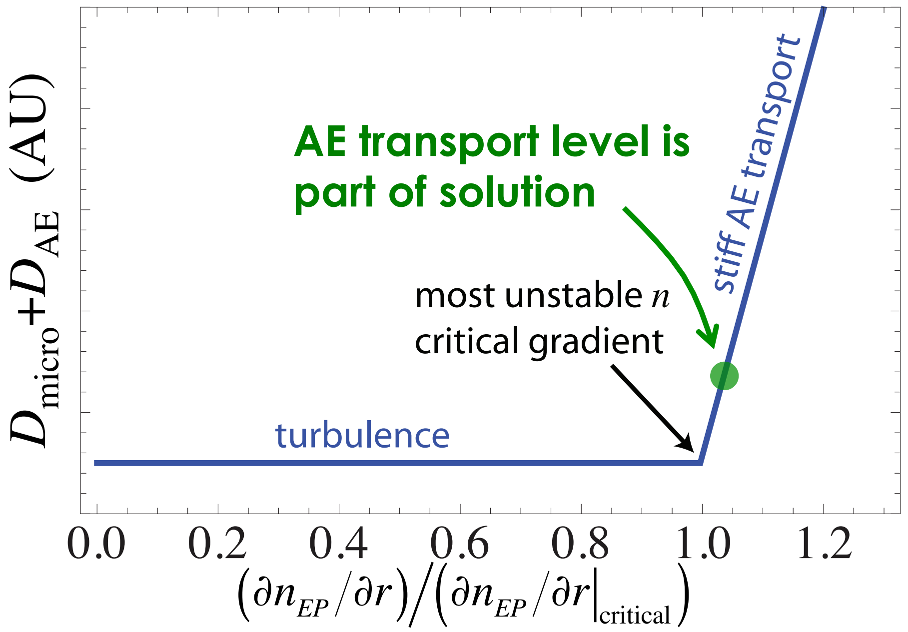
$$S = n_{\text{D}} n_{\text{T}} \left\langle \sigma \text{v} \right\rangle_{\text{DT}}$$

fusion source

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

classical slowing-down density

Gaffey 1976



---

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

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

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

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

fusion or beam source

slowing-down sink (plasma heating)

Diffusive EP flux:

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

D_{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**.

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

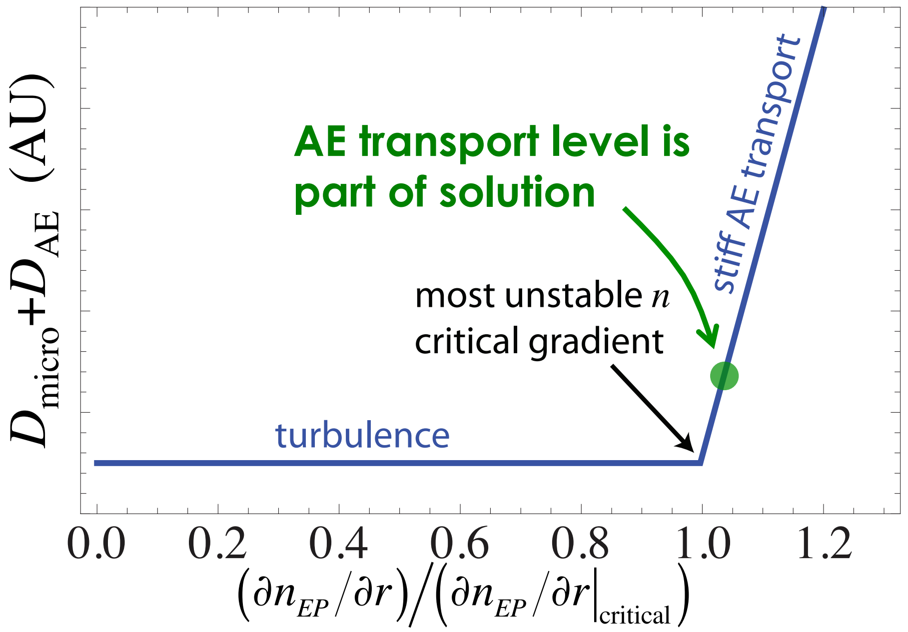
$$S = n_{\mathrm{D}} n_{\mathrm{T}} \langle \sigma \mathrm{v} \rangle_{\mathrm{DT}}$$

fusion source

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

classical slowing-down density

Gaffey 1976

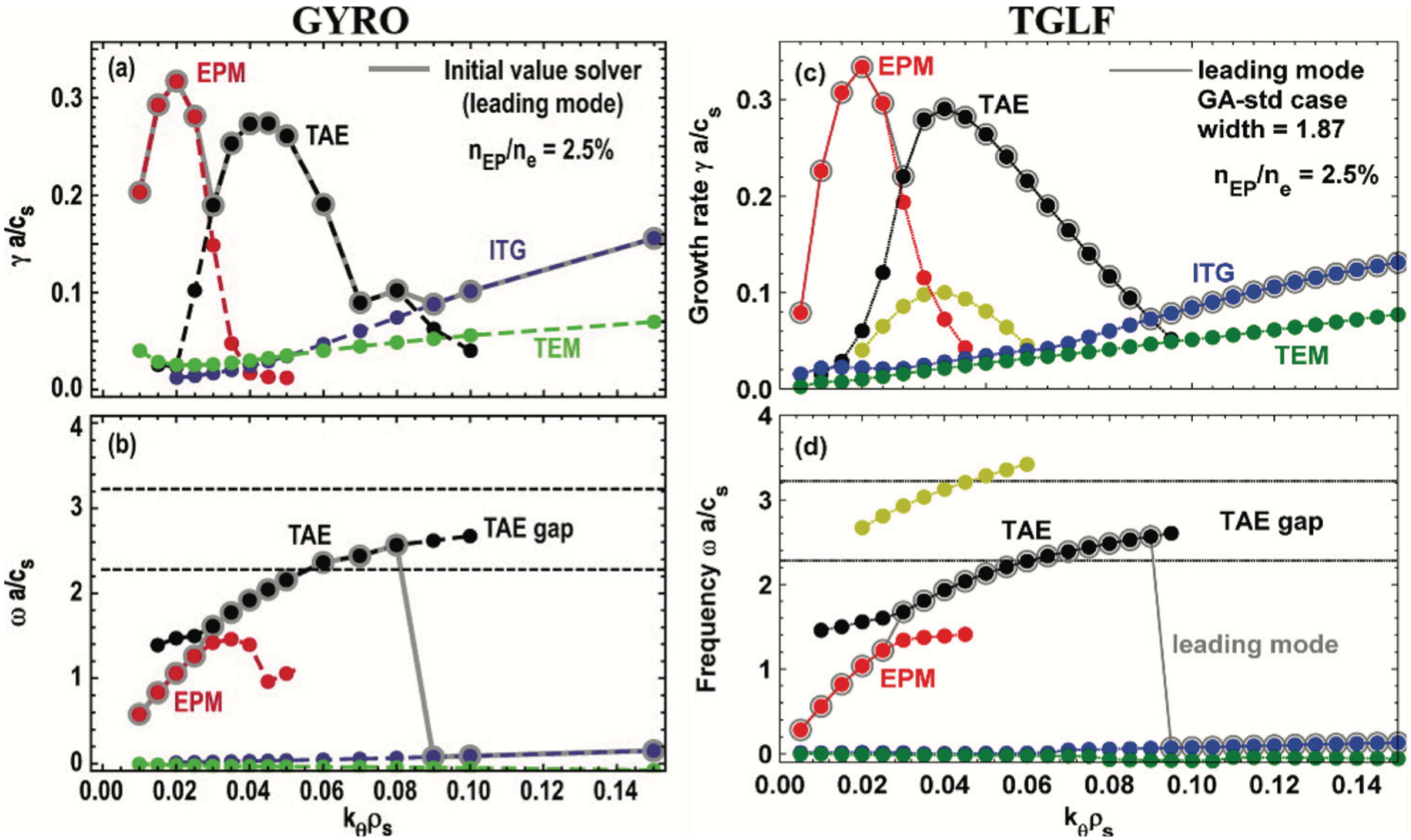


---

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

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

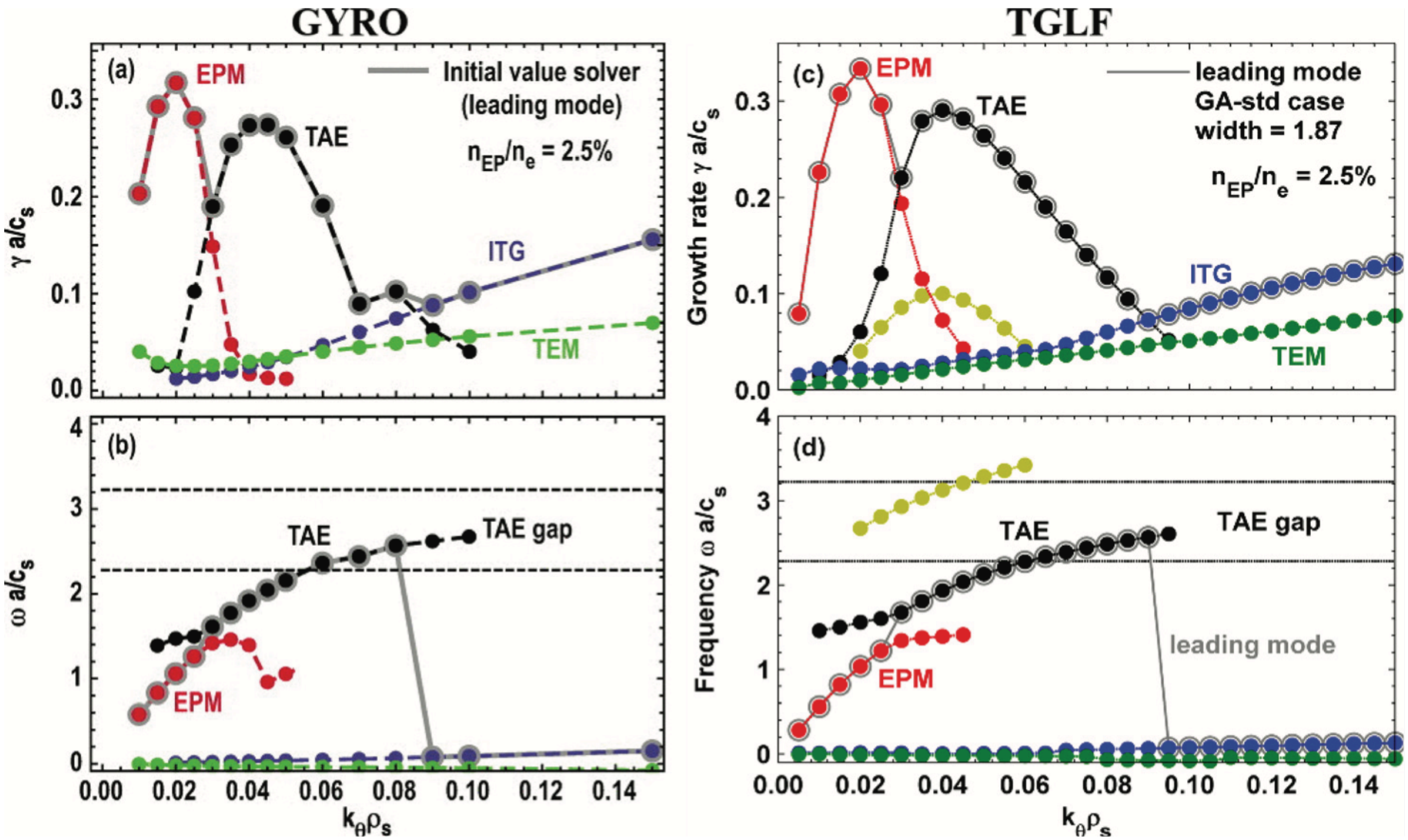
TGLFEP code uses the gyro-Landau fluid TGLF model to find the AE-EP critical gradient where $\gamma_{AE} \rightarrow 0$



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

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

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 **>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.

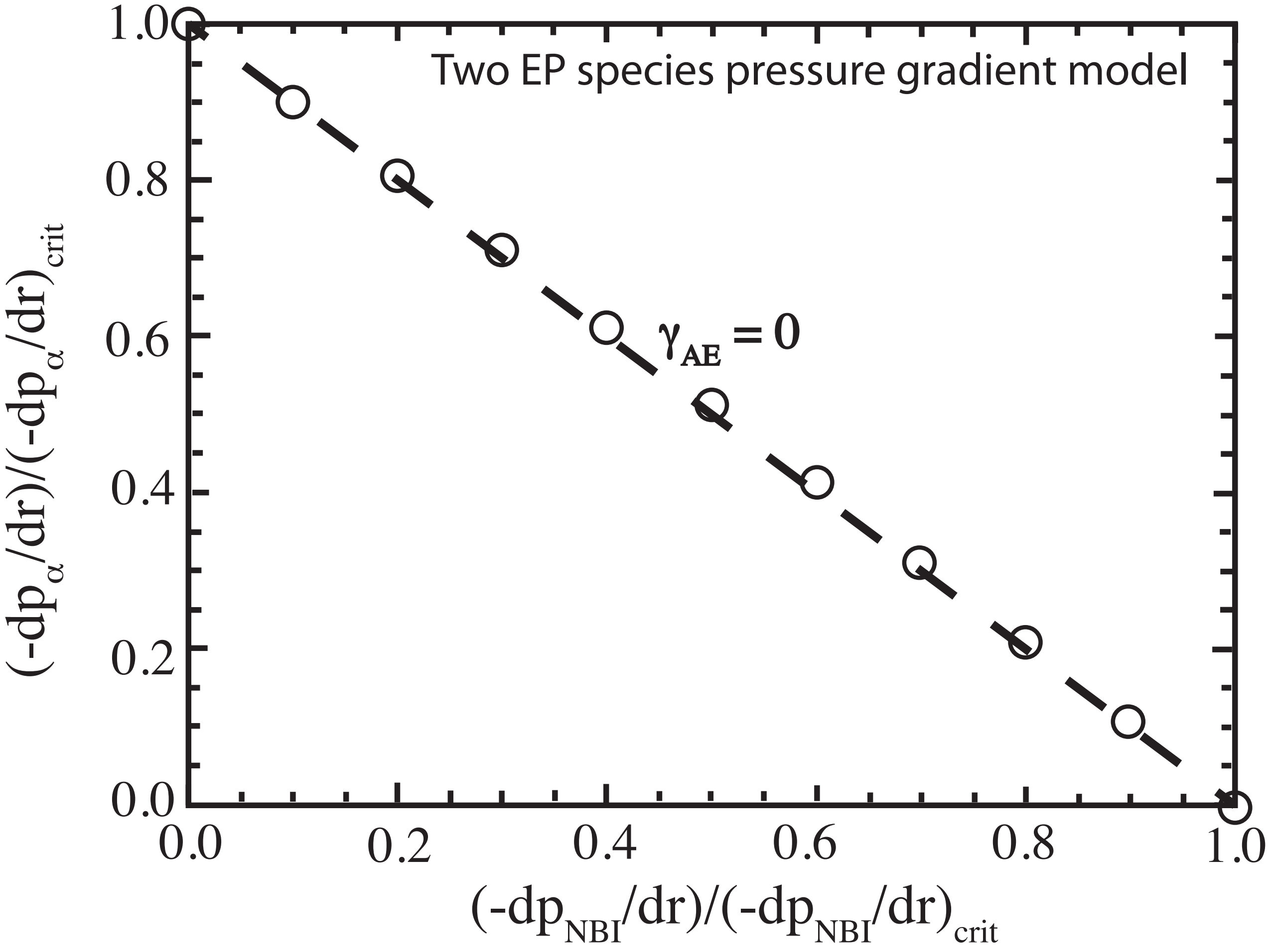
$$\boxed{\sum_i \frac{dp_i / dr}{(dp_i / dr)_{crit}} \geq 1}$$

[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.

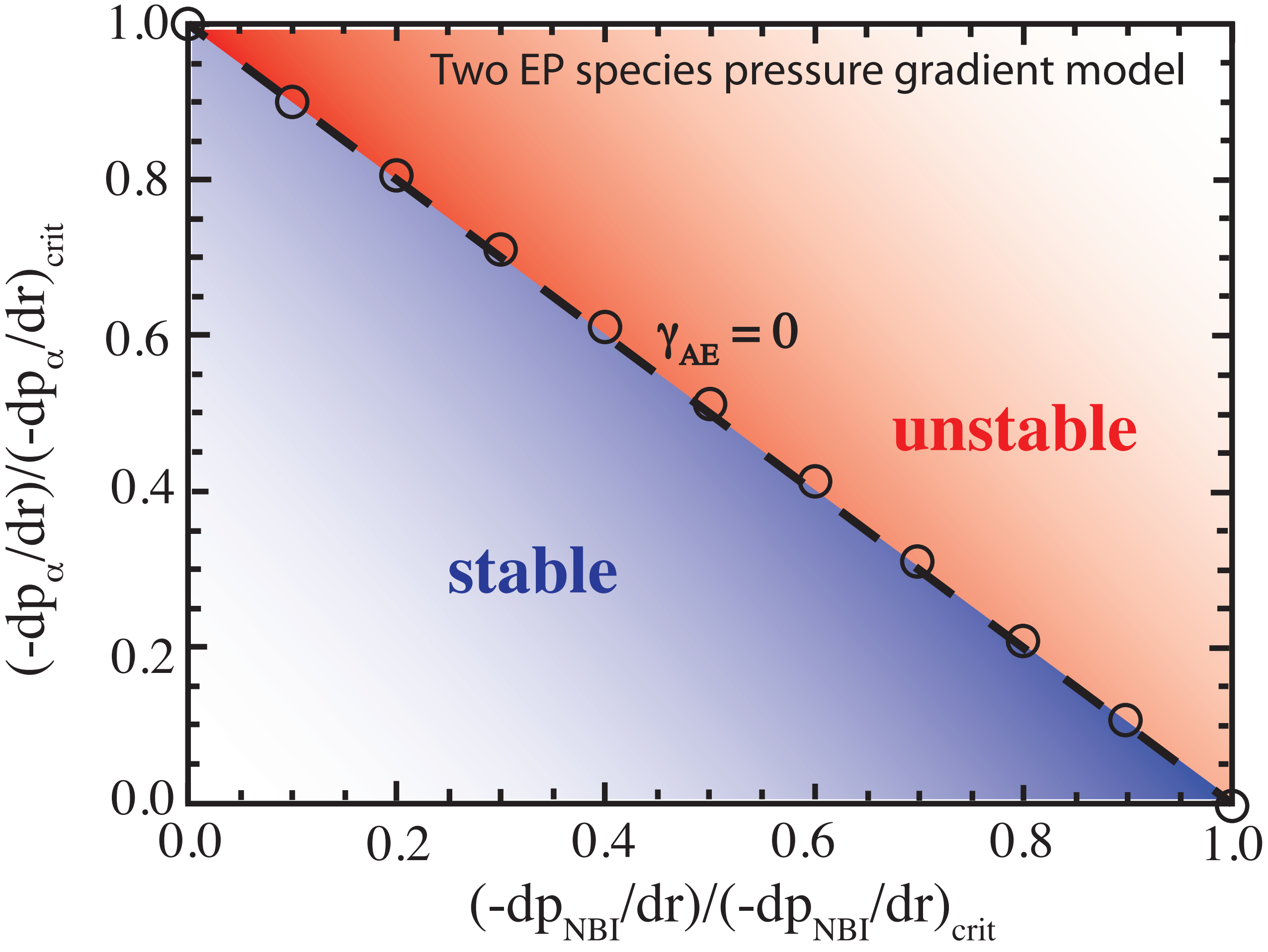
$$\sum_i \frac{dp_i / dr}{(dp_i / dr)_{crit}} \geq 1$$



[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.



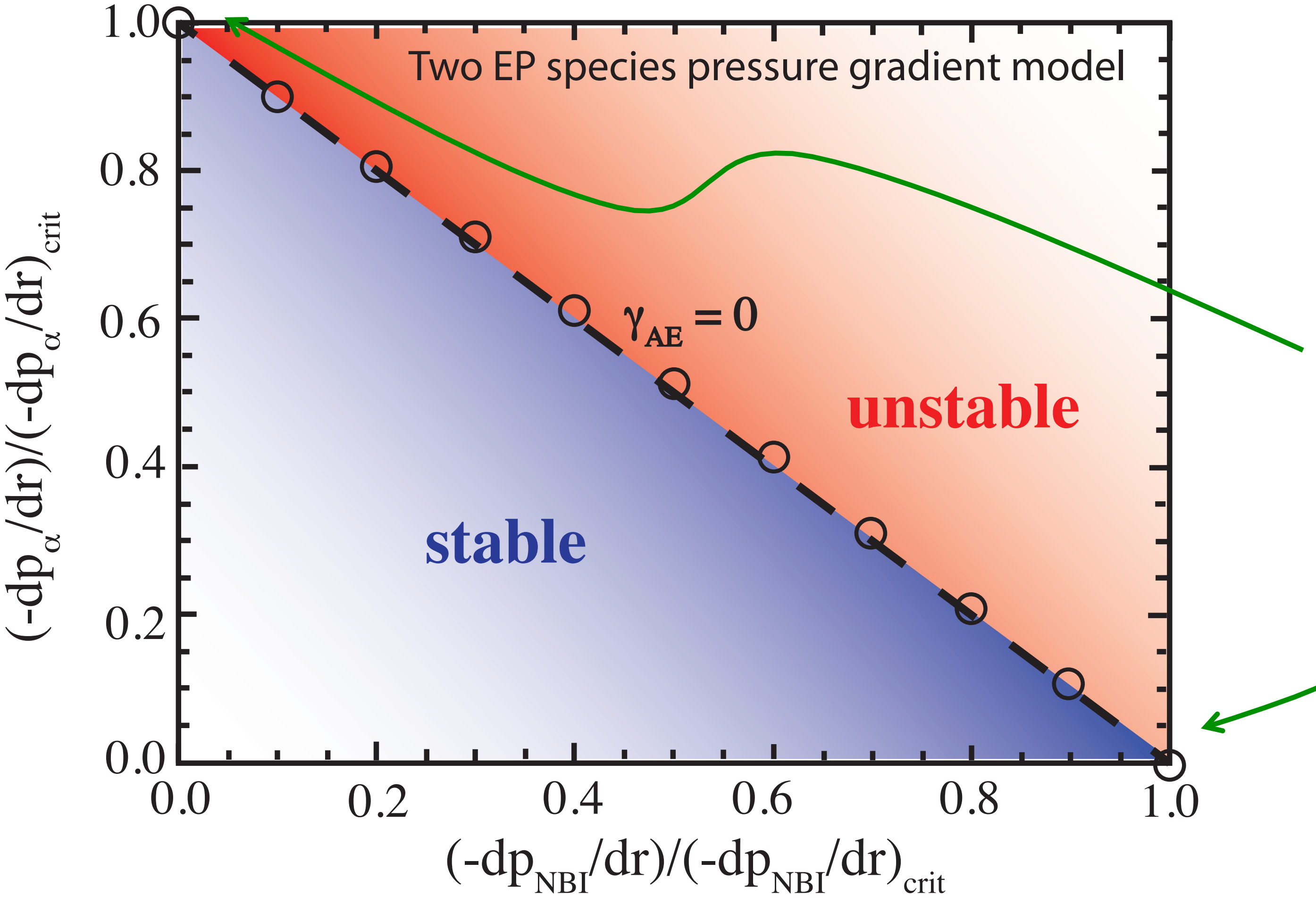
$$\sum_i \frac{dp_i / dr}{(dp_i / dr)_{crit}} \geq 1$$

[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.

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



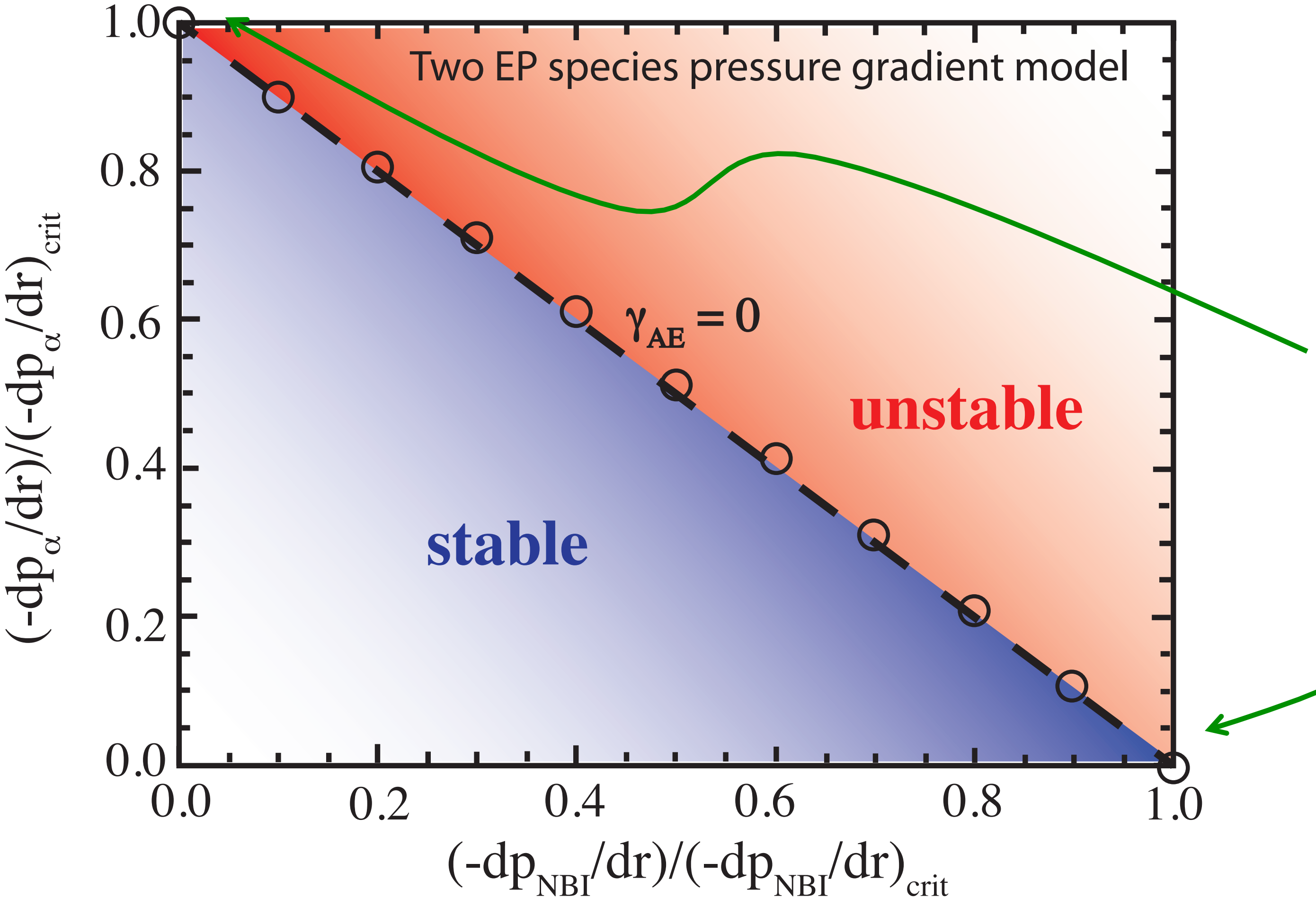
The two isolated critical gradients specify the two-species critical gradient for **coupled transport**.

[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)

Outline

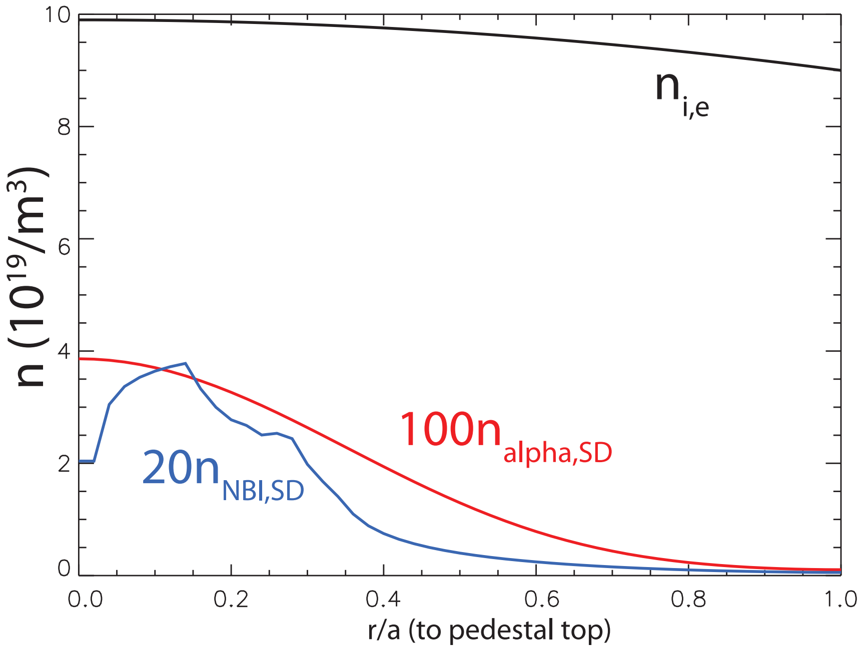
I. Introduction: Energetic Particle (EP) transport by Alfvén eigenmodes (AEs) and the need for reduced models

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

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

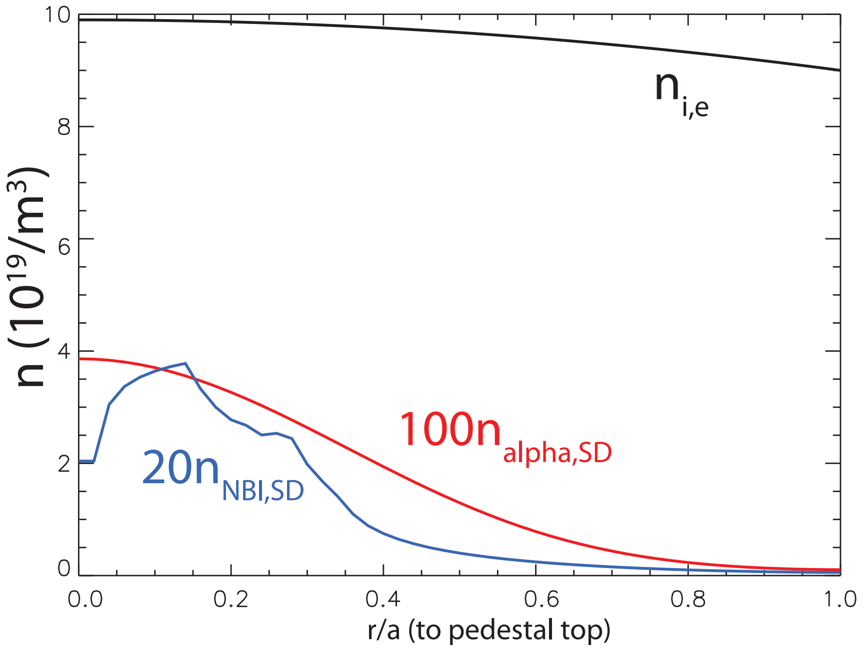
IV. Summary

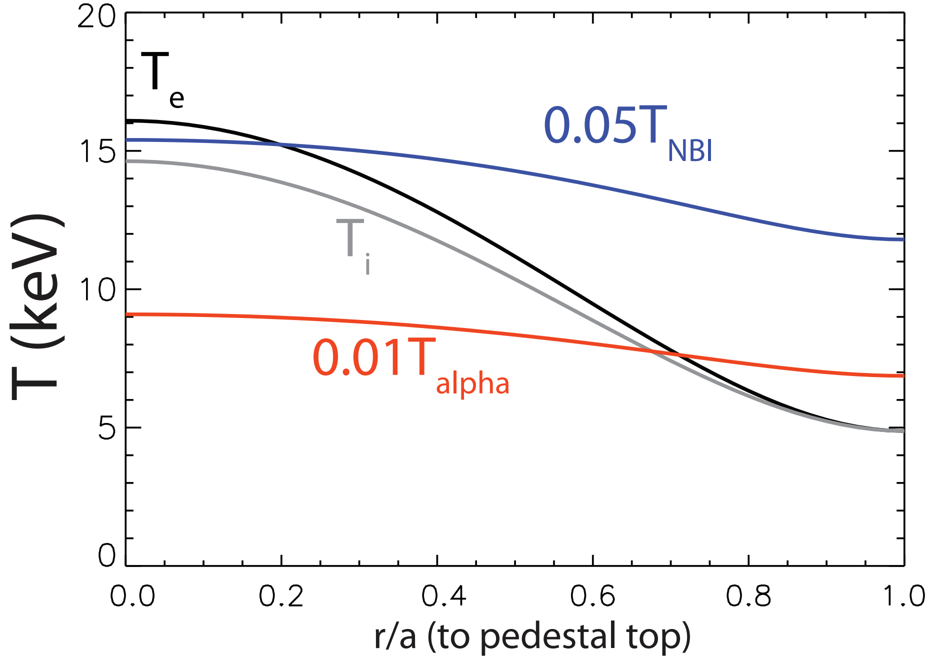
We consider a 30 MW Q≈10 ITER profile prediction based on EPED1 and tGYRO TGLF core transport[1]



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

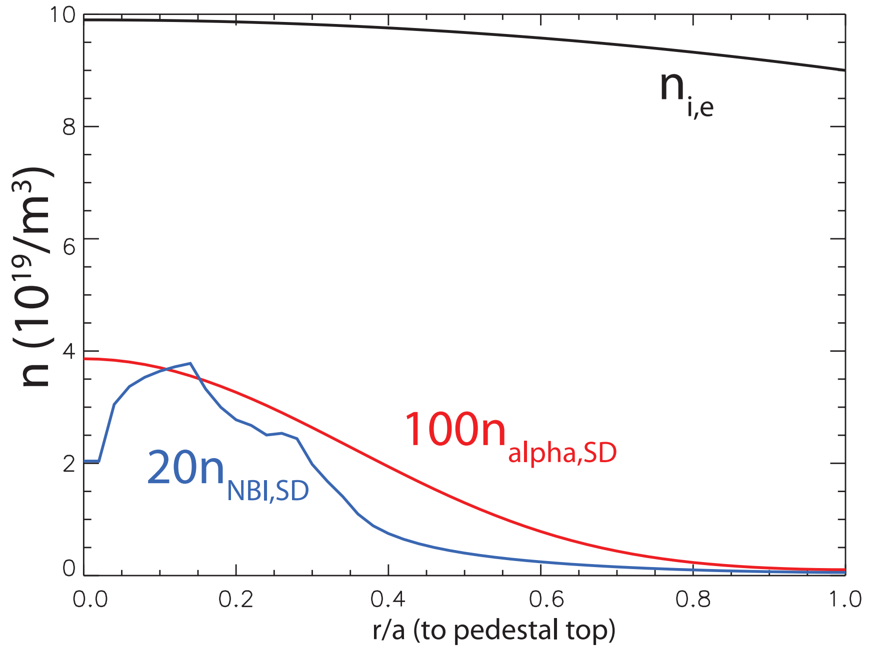
We consider a 30 MW Q≈10 ITER profile prediction based on EPED1 and tGYRO TGLF core transport[1]

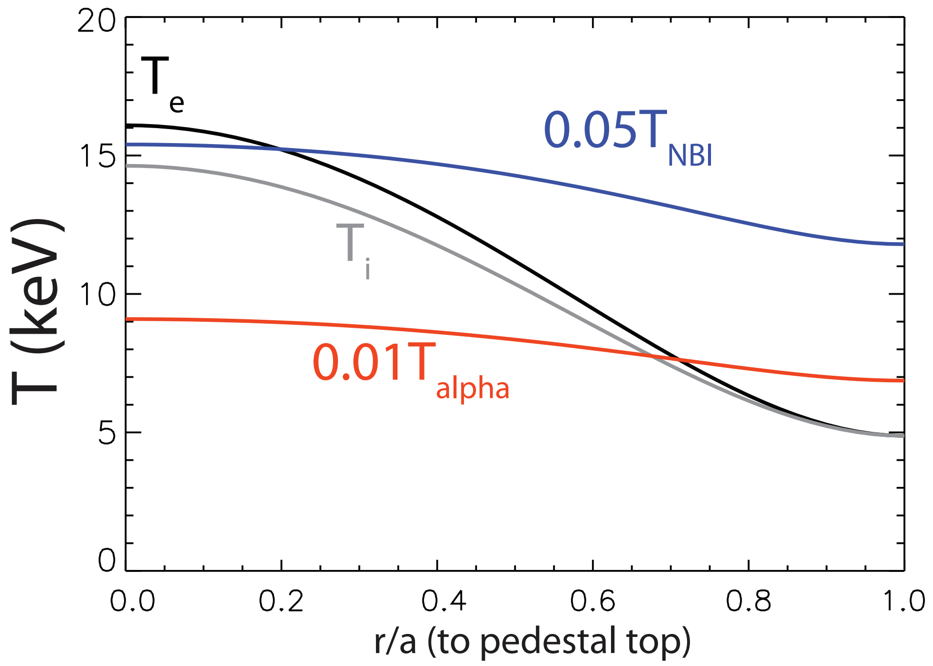




[1] J. Kinsey, G.M. Staebler, J. Candy, R.E. Waltz, and R. Budny, Nucl. Fusion **51**, 083001 (2011)

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

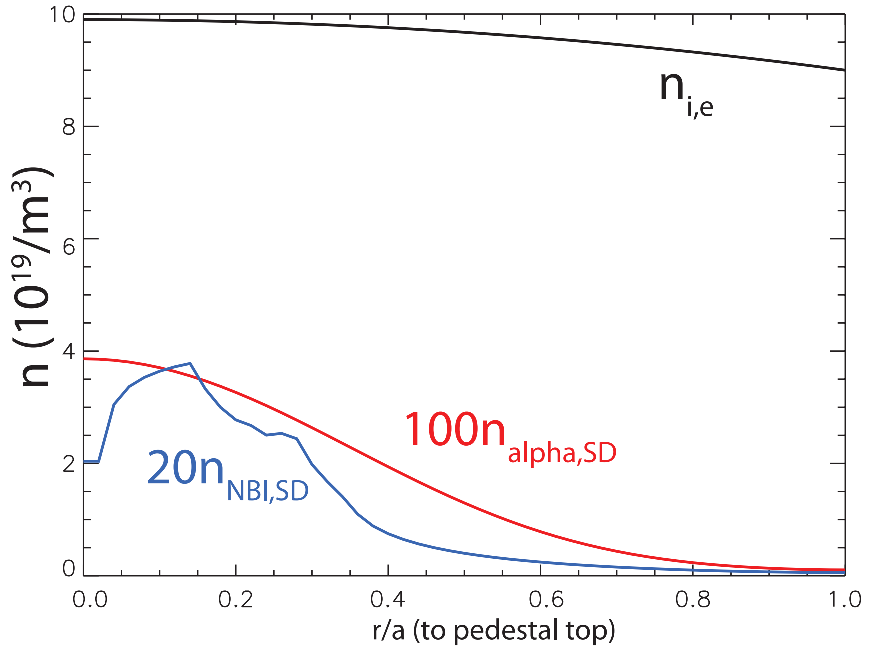


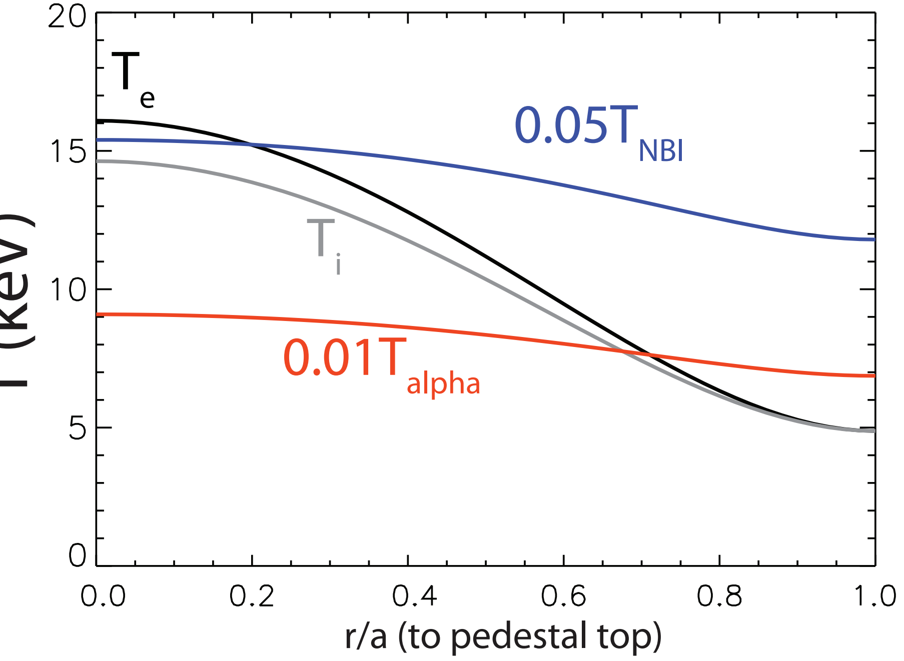


EP β fraction of about 30% → AEs robustly unstable

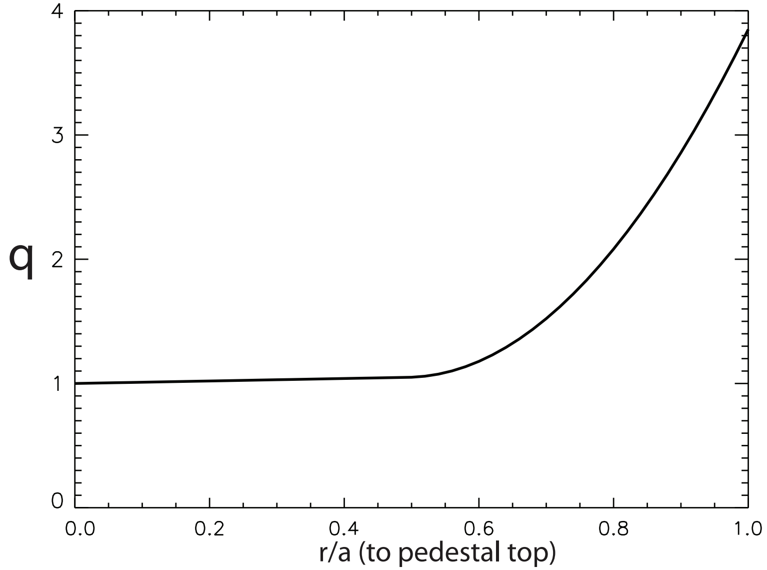
[1] J. Kinsey, G.M. Staebler, J. Candy, R.E. Waltz, and R. Budny, Nucl. Fusion **51**, 083001 (2011)

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



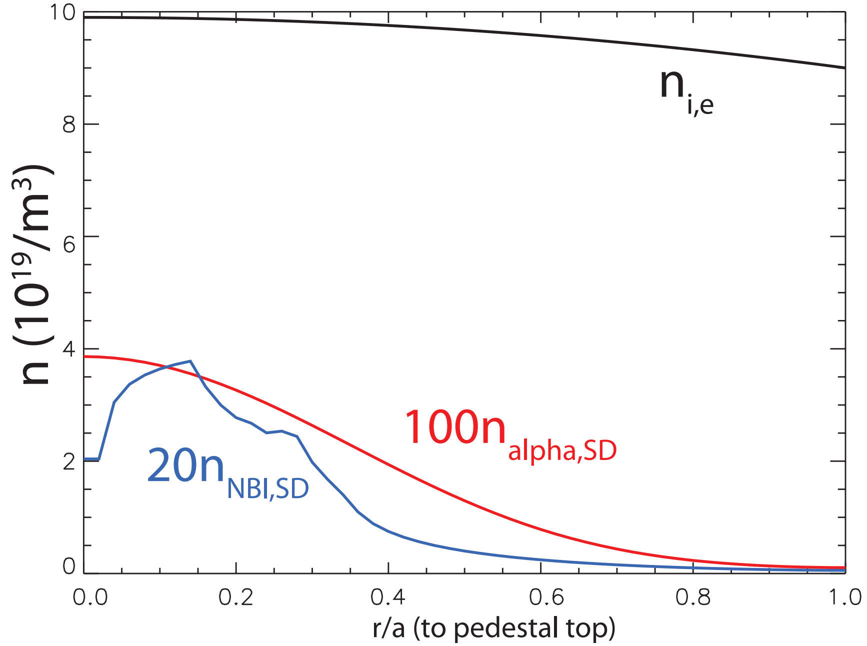


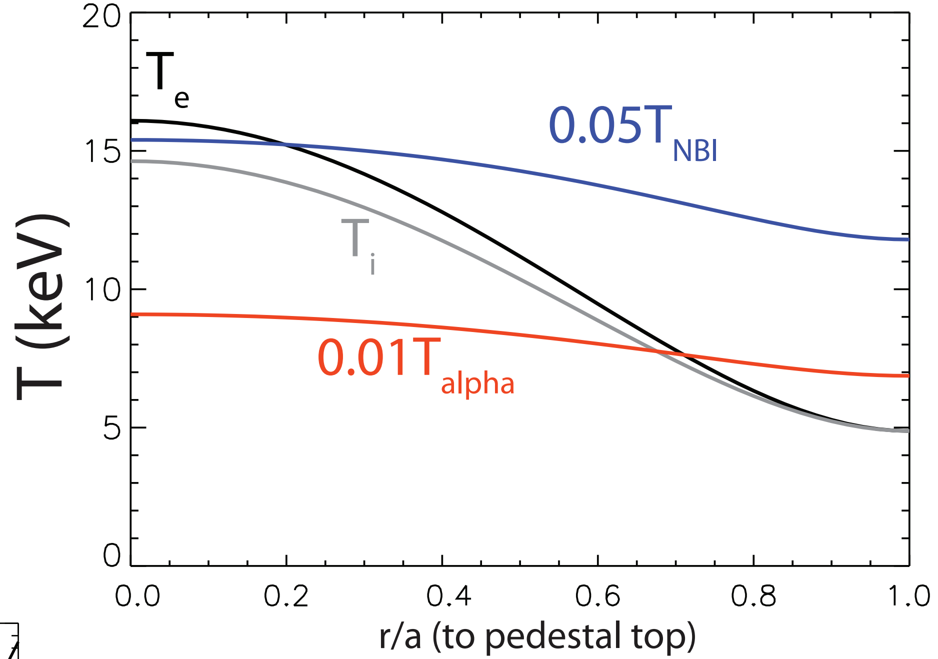
EP β fraction of about 30% → AEs robustly unstable



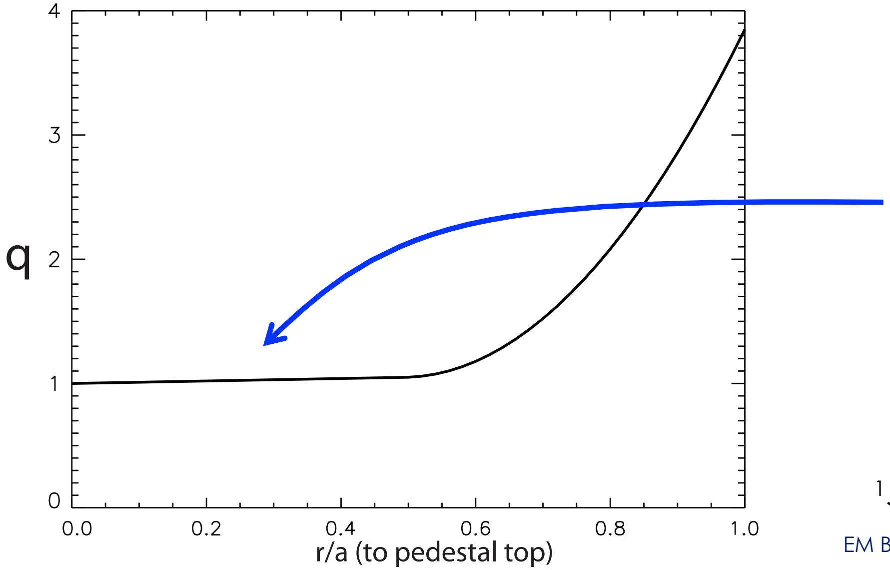
[1] J. Kinsey, G.M. Staebler, J. Candy, R.E. Waltz, and R. Budny, Nucl. Fusion **51**, 083001 (2011)

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





EP β fraction of about 30% → AEs robustly unstable

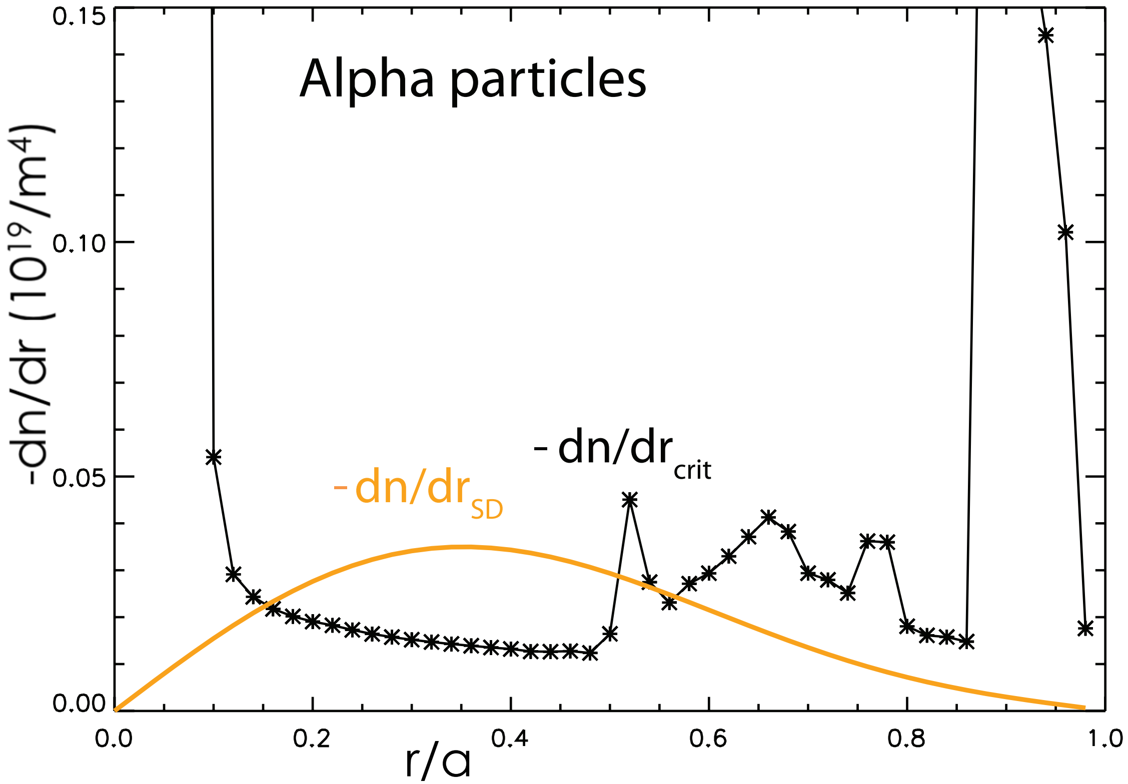


Very weak central shear region (from sawtooth current mixing) proves to be the most AE unstable for the base case scenario with **maximum current drive and current penetration**.

---

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

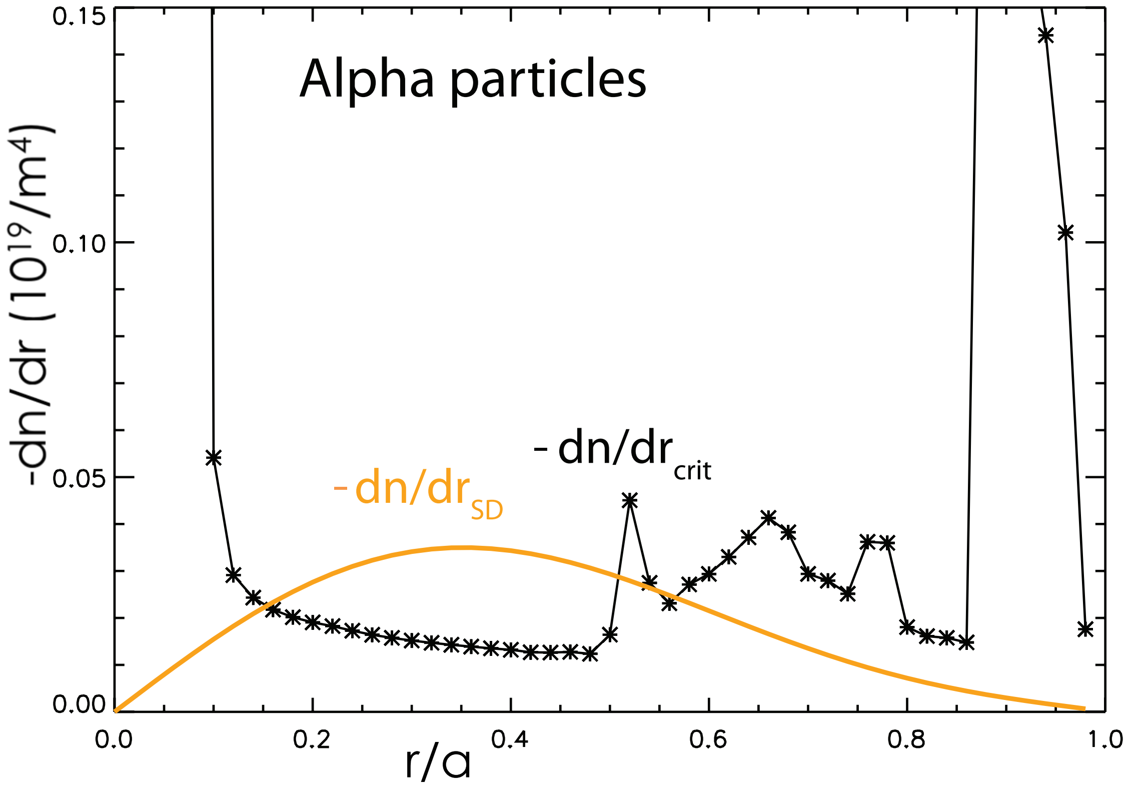
As in 2015 GYRO ITER simulations[1], TGLFEP finds unstable AEs only in the mid core where $-dn/dr_{SD}$>$-dn/dr_{crit}$



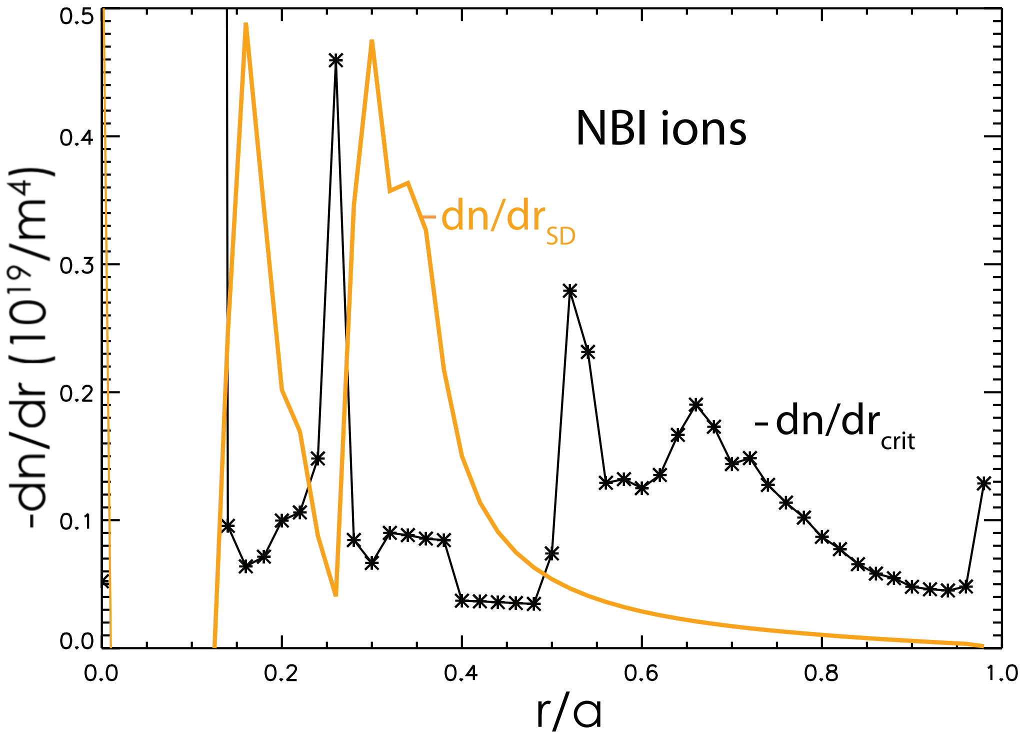
ITER base case

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

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



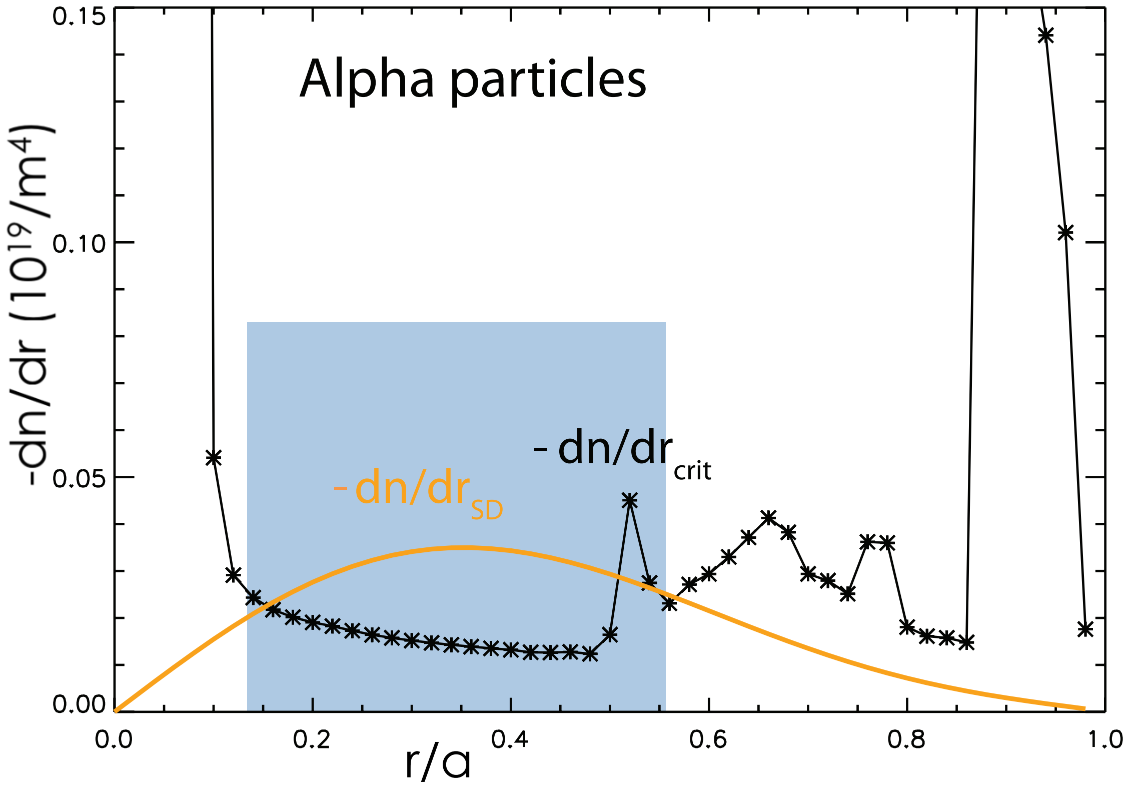
ITER base case



---

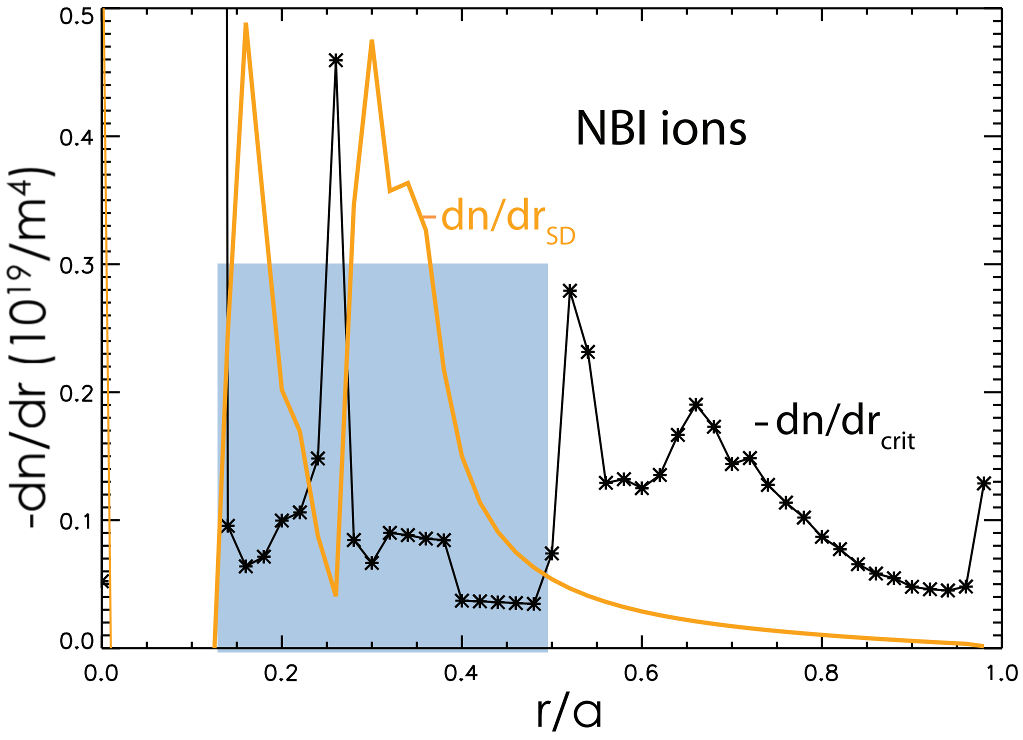
[1] R.E. Waltz, E.M. Bass, W.W. Heidbrink, and M.A. VanZeeland, Nucl. Fusion **55**, 123012 (2011)

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



Nominally unstable region

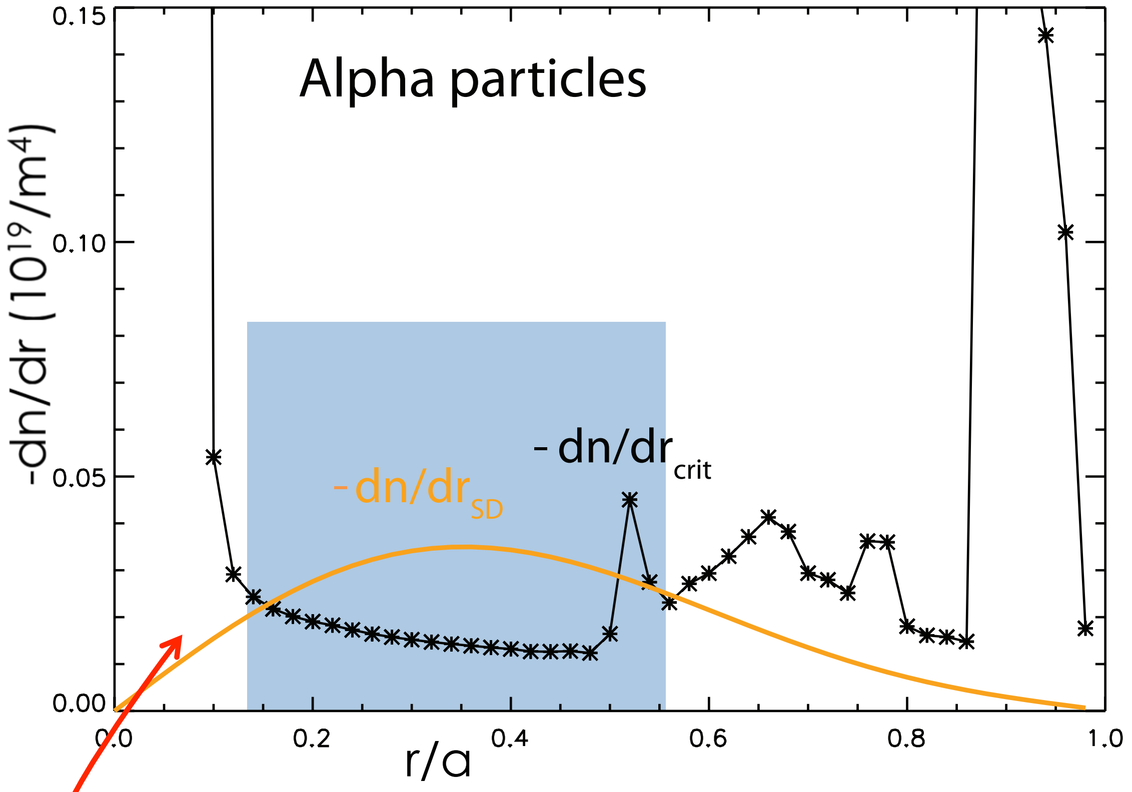
ITER base case



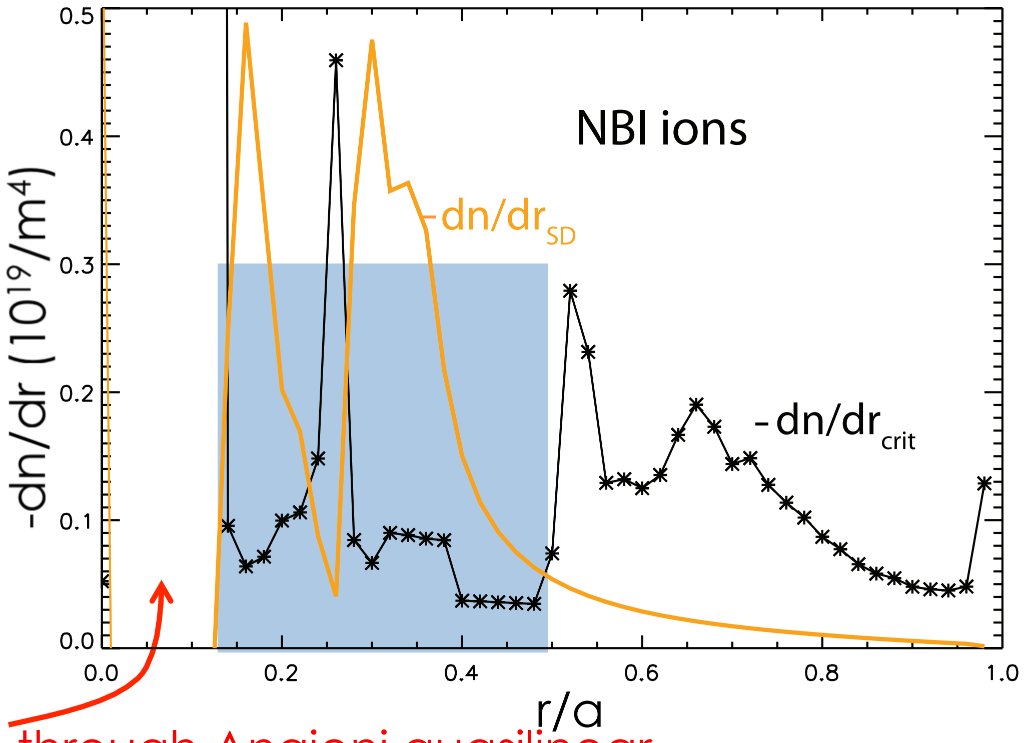
---

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

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



ITER base case

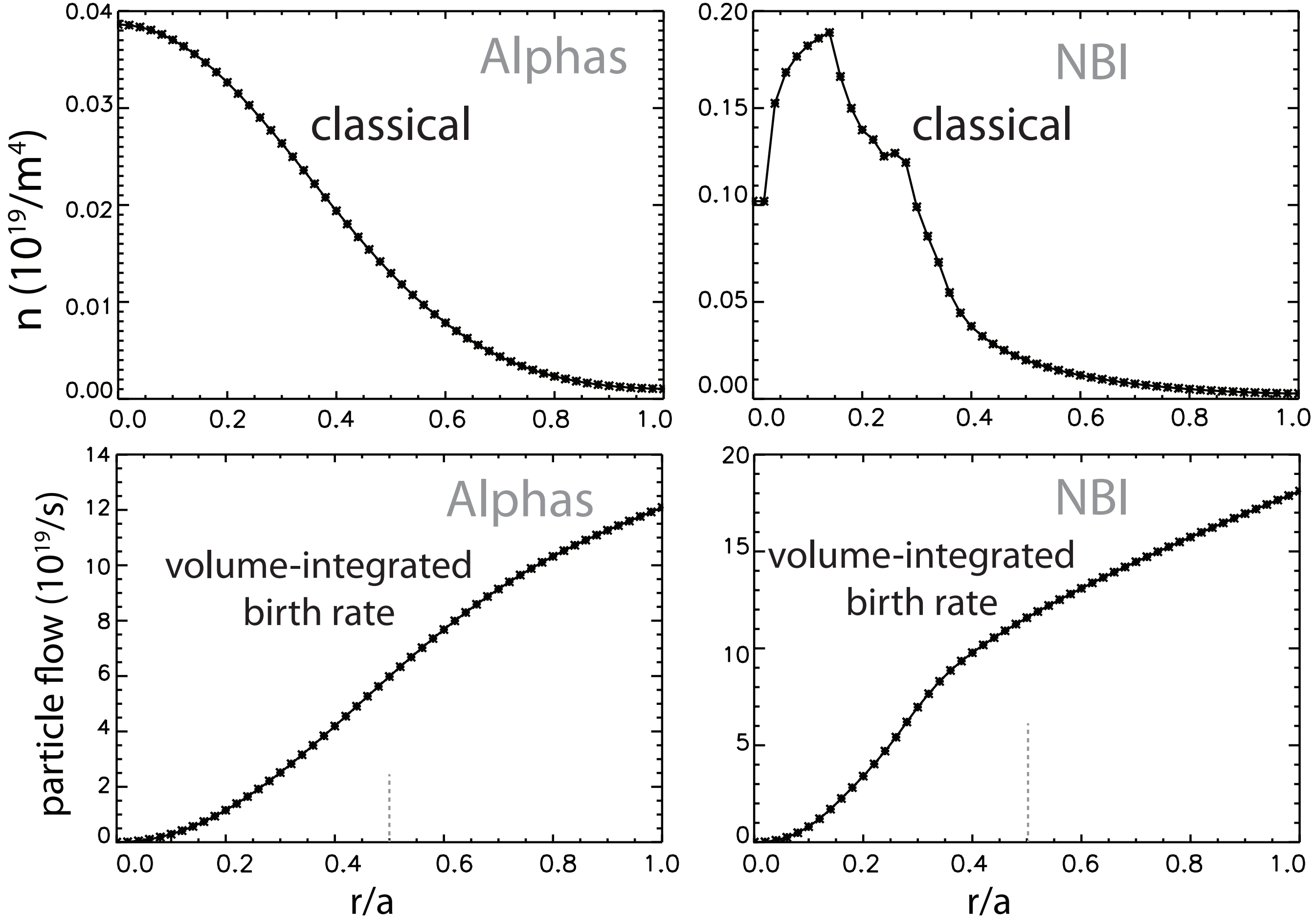


Nominally unstable region

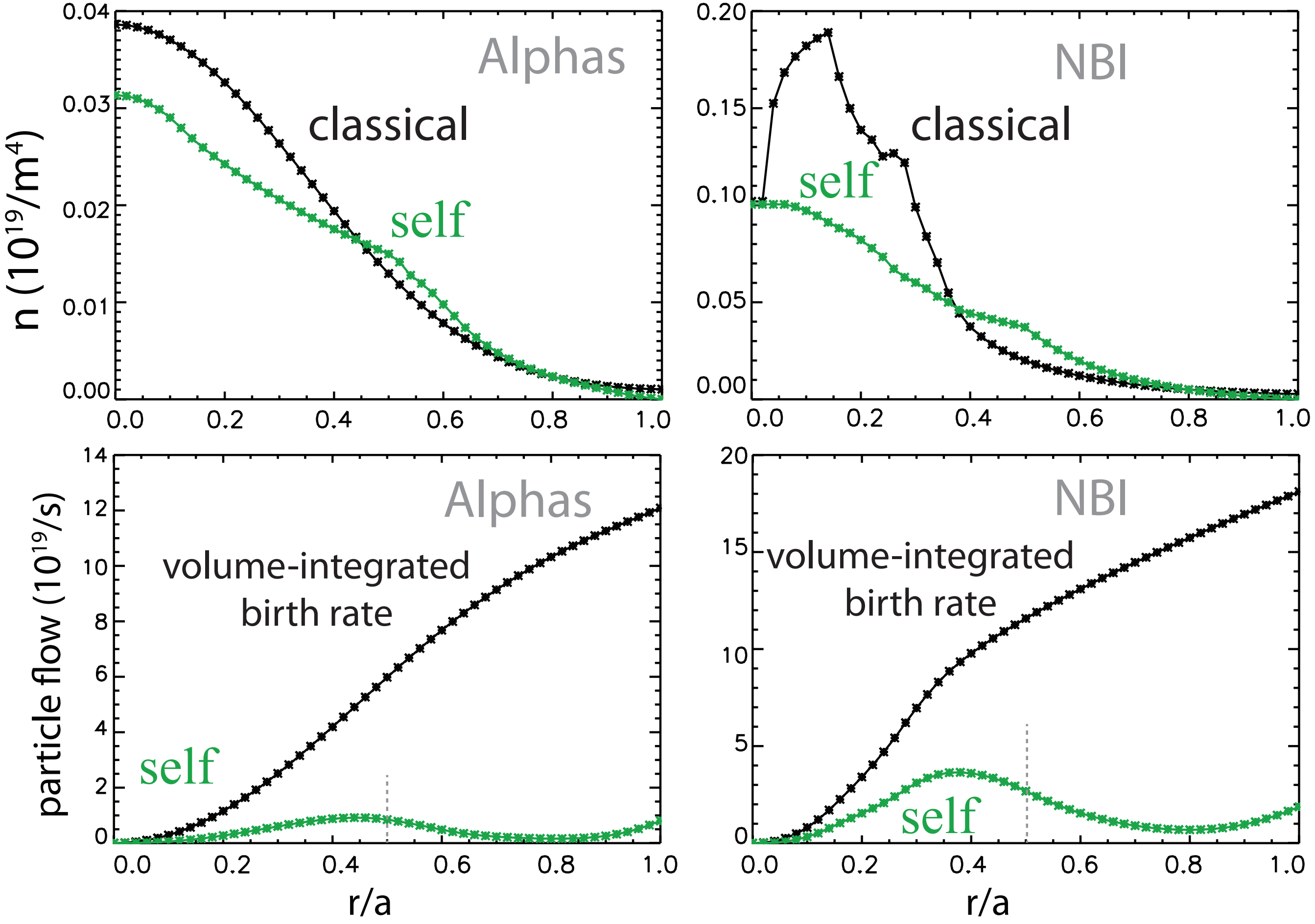
Transport of EPs by background processes, through Angioni quasilinear ratio χ_{EP}/χ_i, depletes core into the "hole" made by CGM AE transport.

[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 !

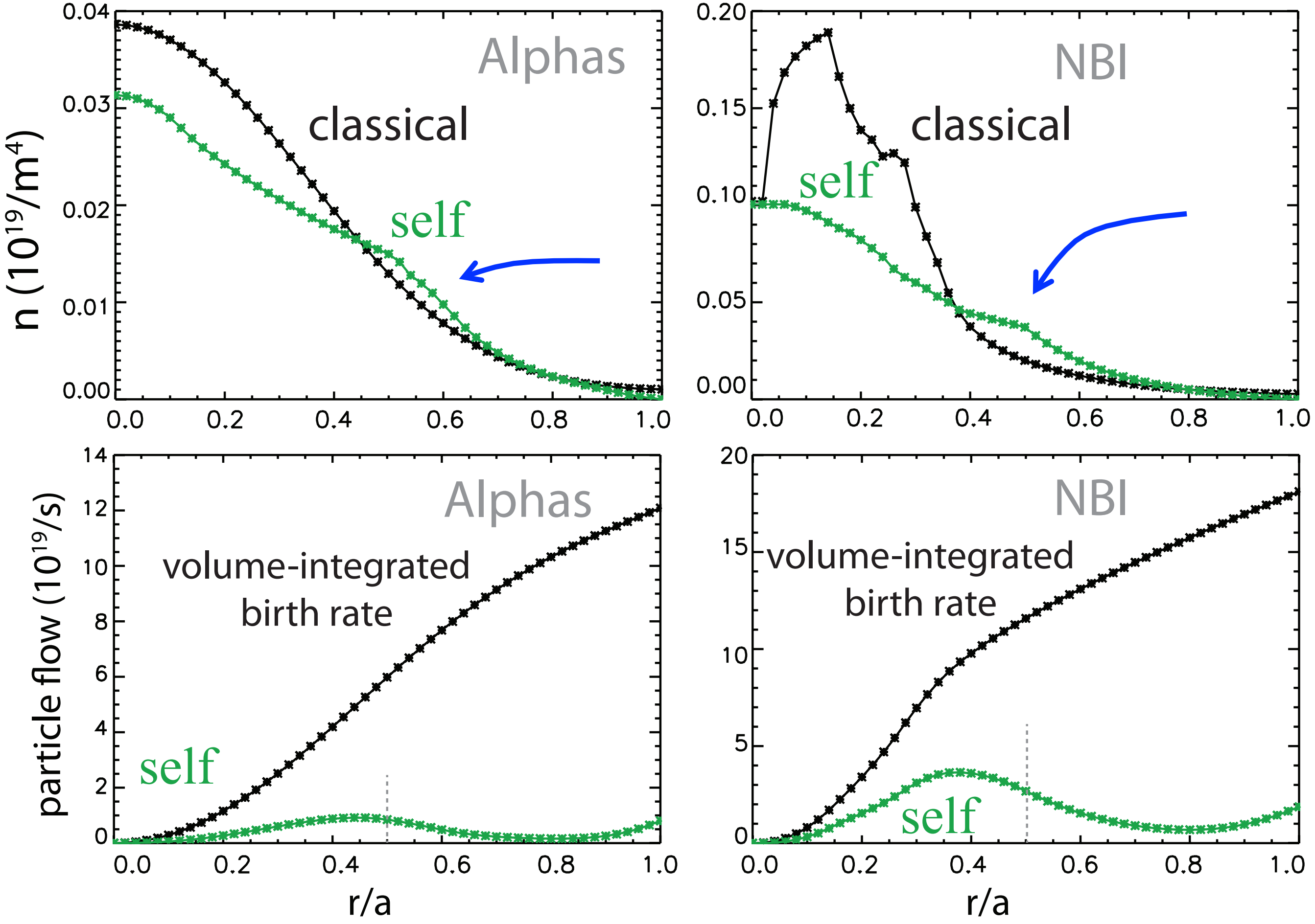


Coupled alpha and NBI drive nearly doubles confinement loss from mid core. Net edge loss is small !



self: Each EP species drives only its own transport

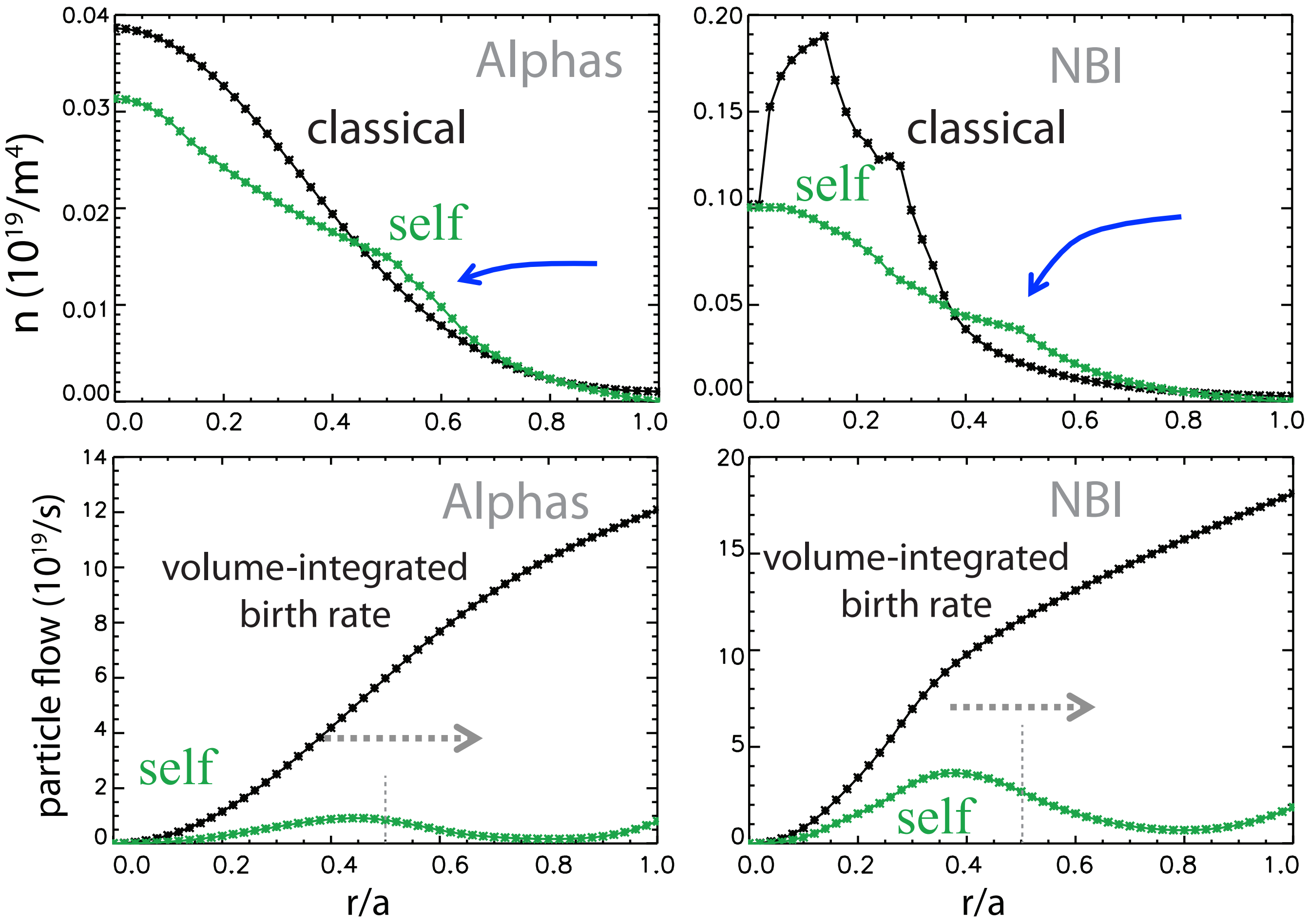
Coupled alpha and NBI drive nearly doubles confinement loss from mid core. Net edge loss is small !



Mid-core AEs redeposit EPs outward

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 !



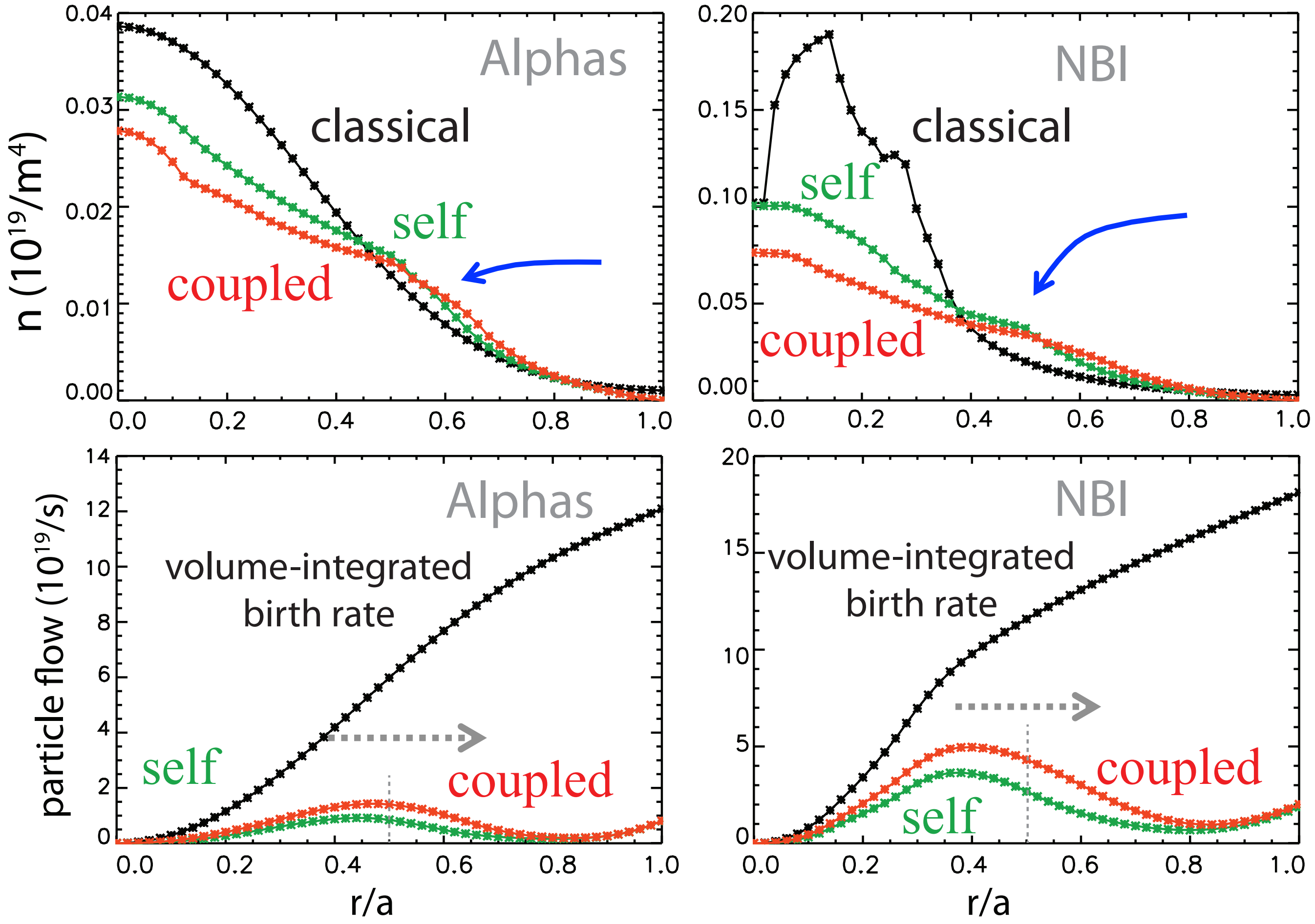
Mid-core AEs redeposit EPs outward

self: Each EP species drives only its own transport

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

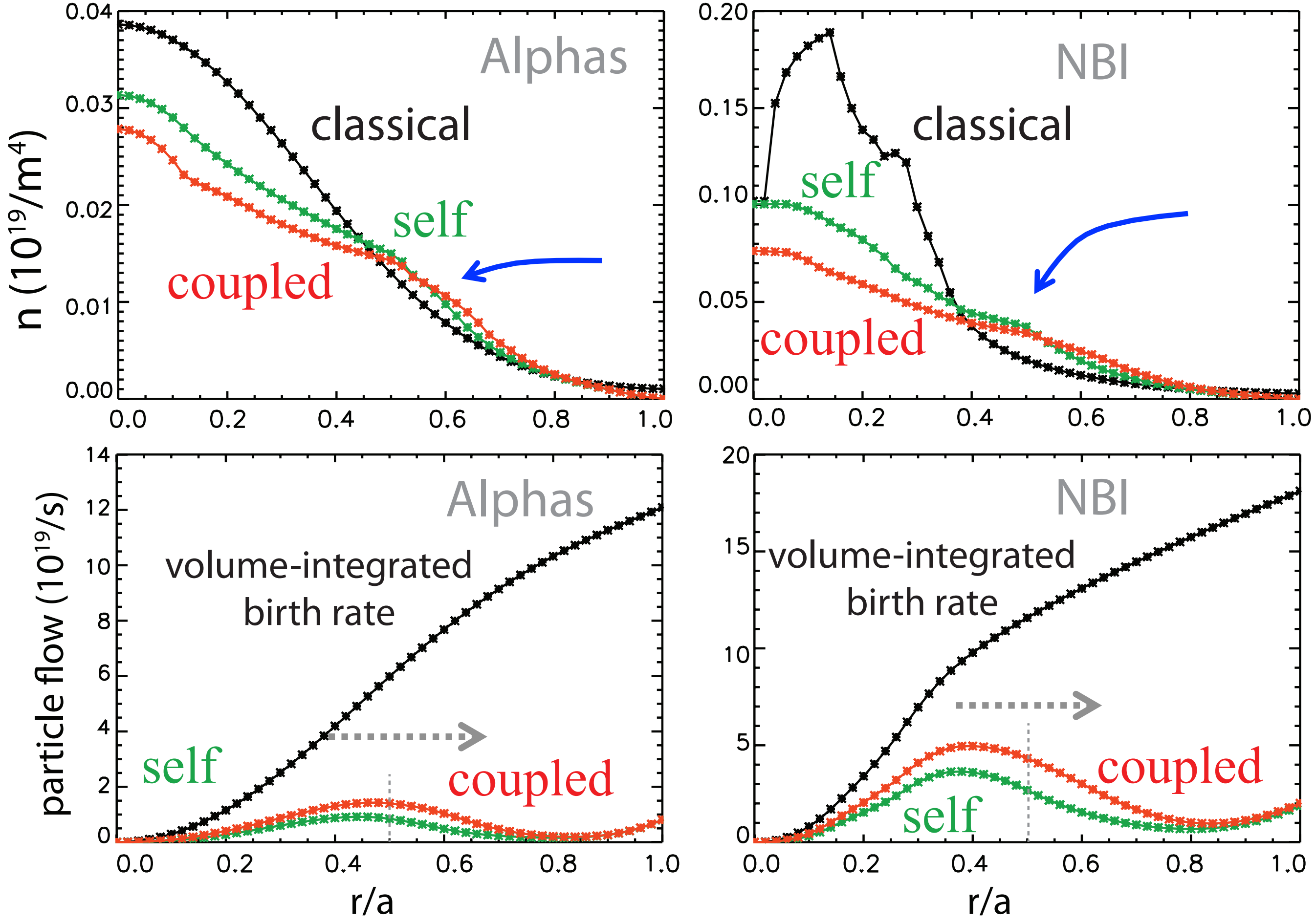
self: Each EP species drives only its own transport

coupled: Simultaneous drive transports both species.

EPs redistributed from
inner core to outer core

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

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

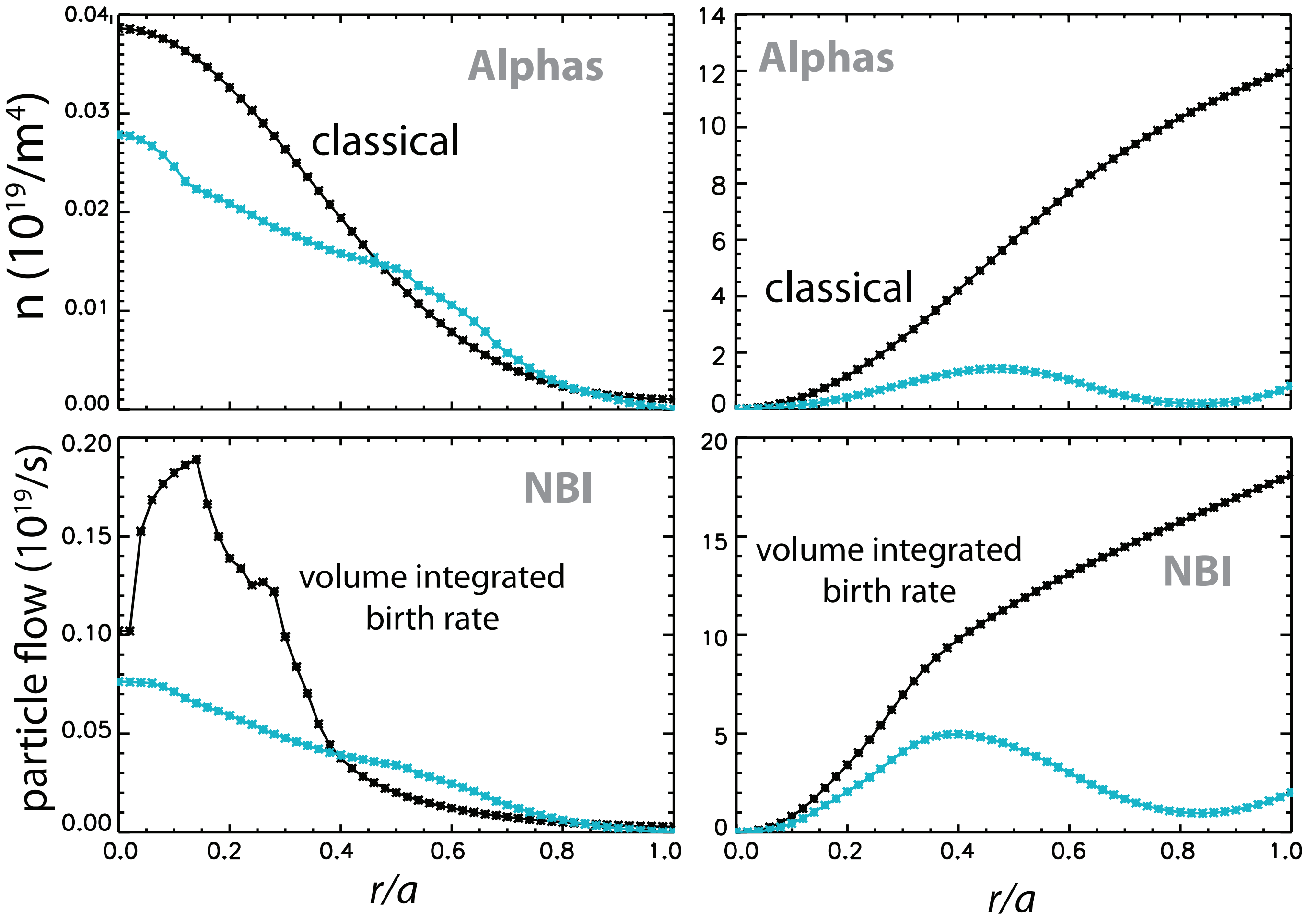
coupled: Simultaneous drive transports both species.

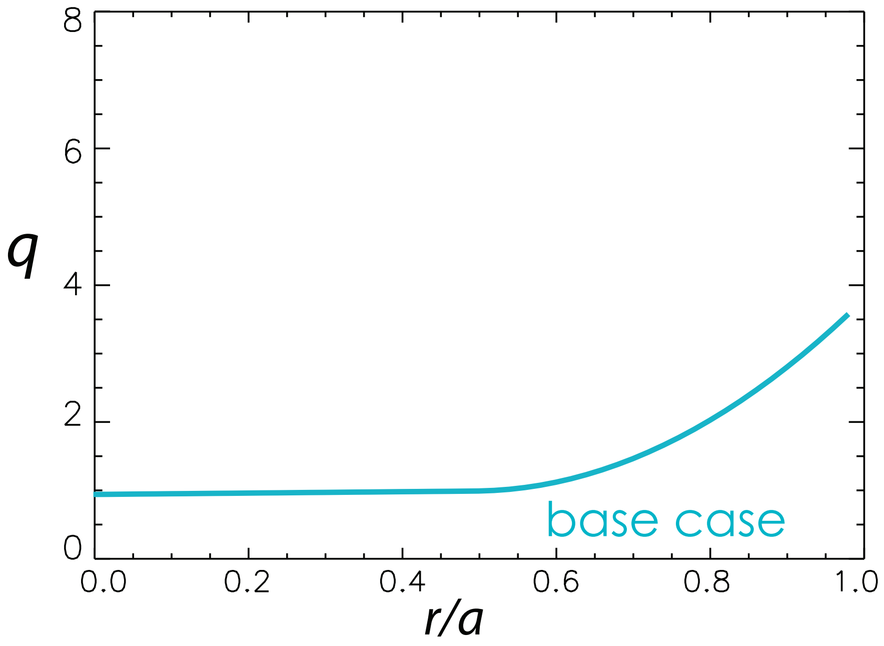
EPs redistributed from
inner core to outer core

	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

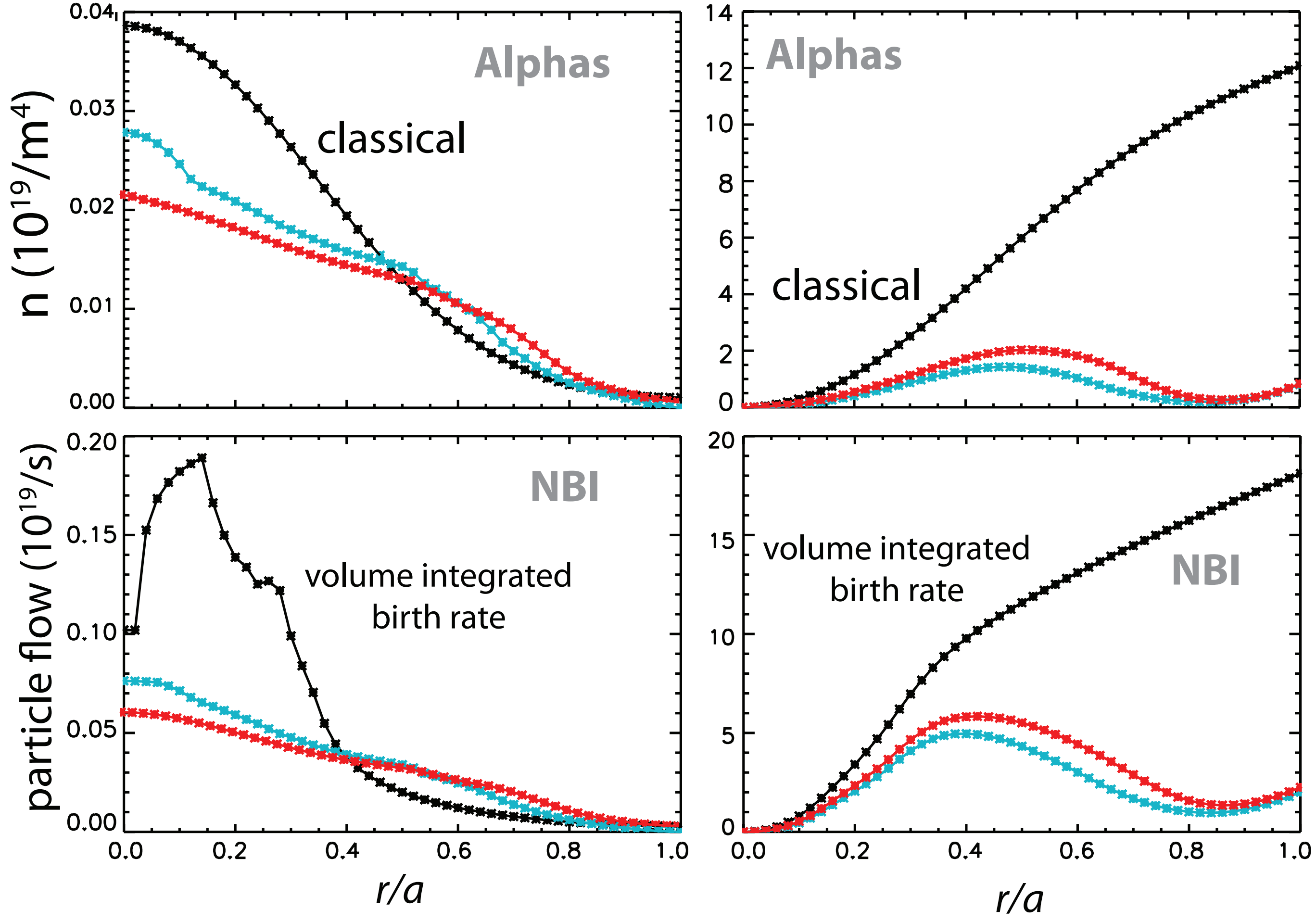


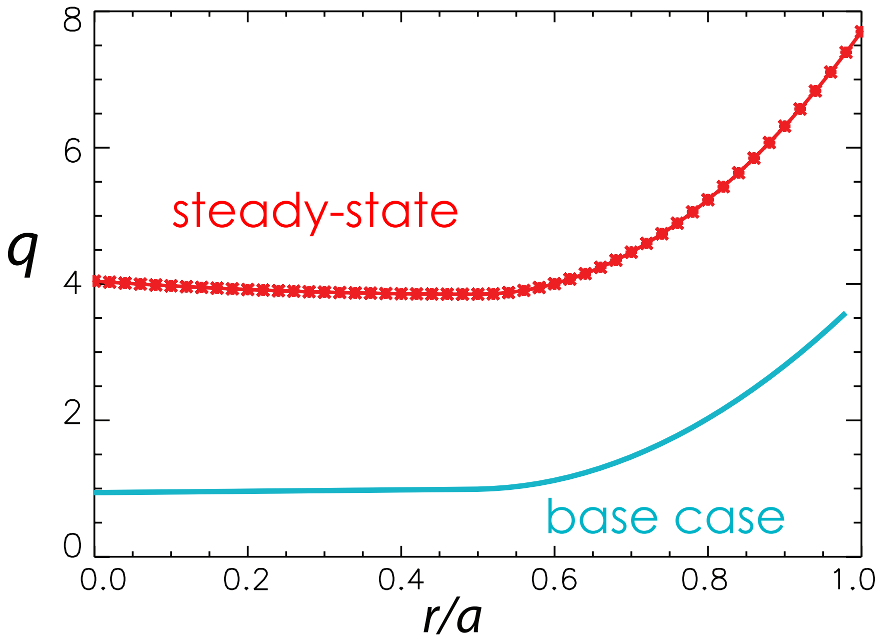


EM Bass/IAEA-FEC/October. 2018

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

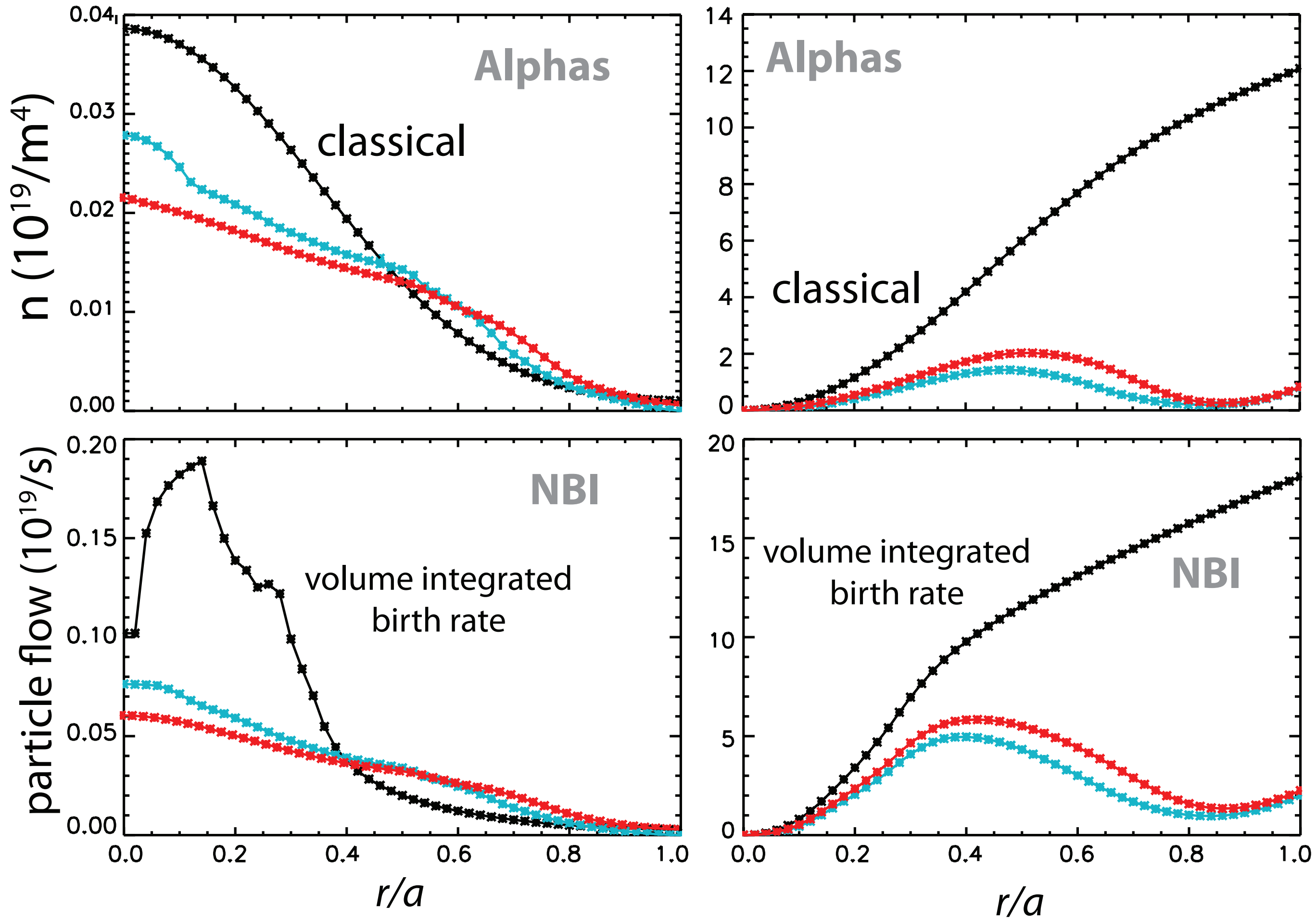
Steady-state (non-inductive current drive) case has 7.5 MA (half base-case value) current and weak penetration.

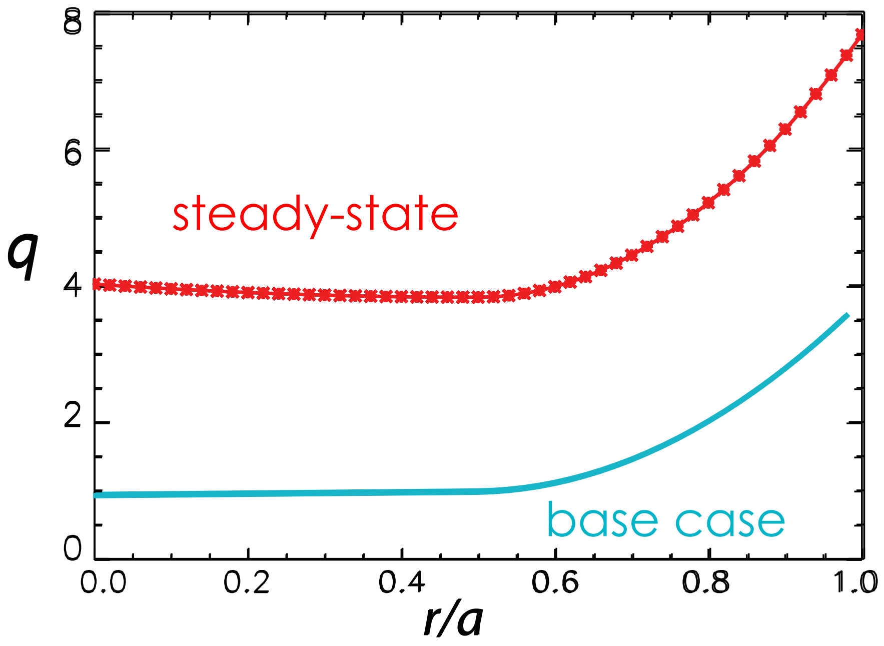




High q and low shear are destabilizing, but shear is more important

Steady-state (non-inductive current drive) case has 7.5 MA (half base-case value) current and weak penetration.

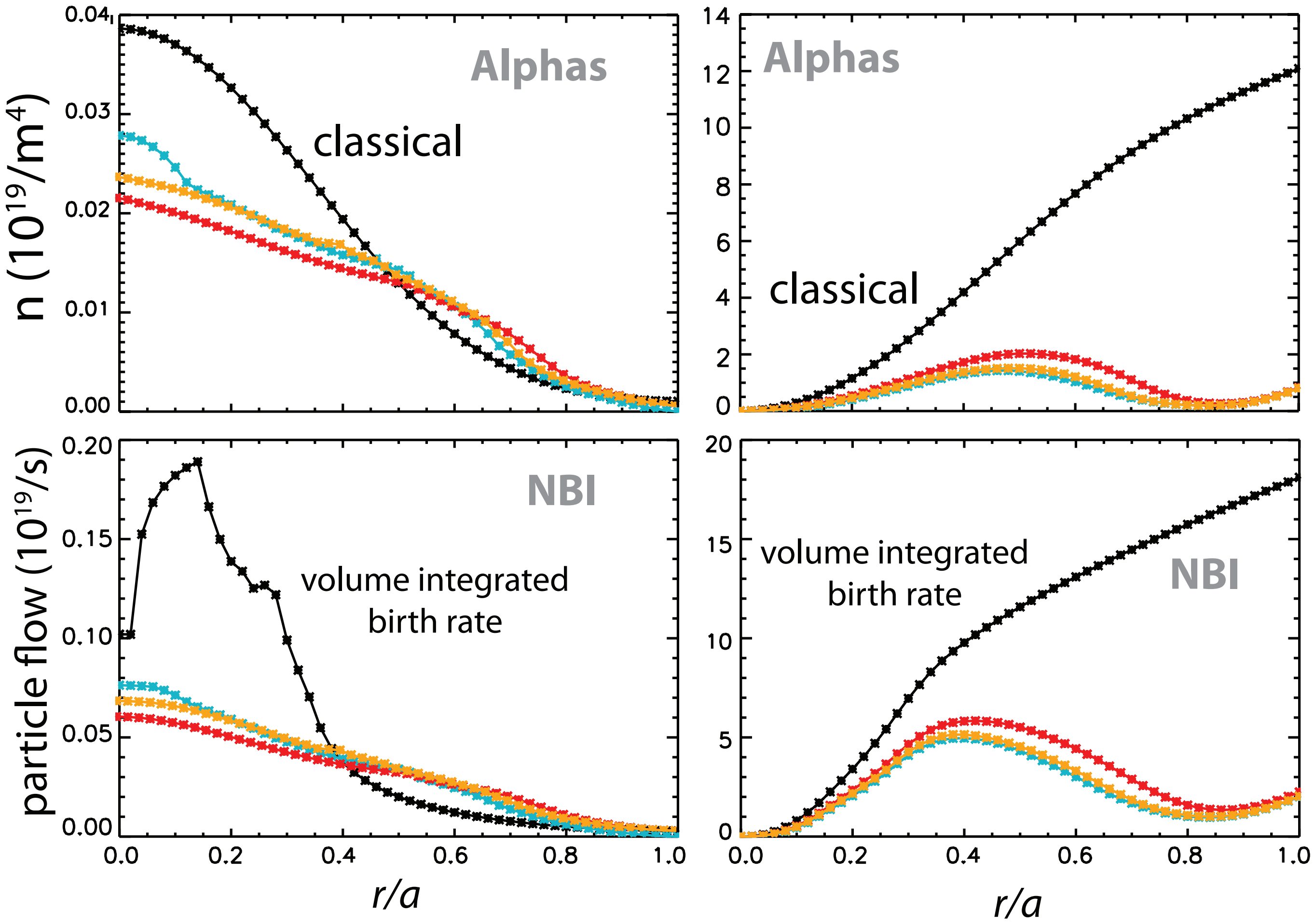


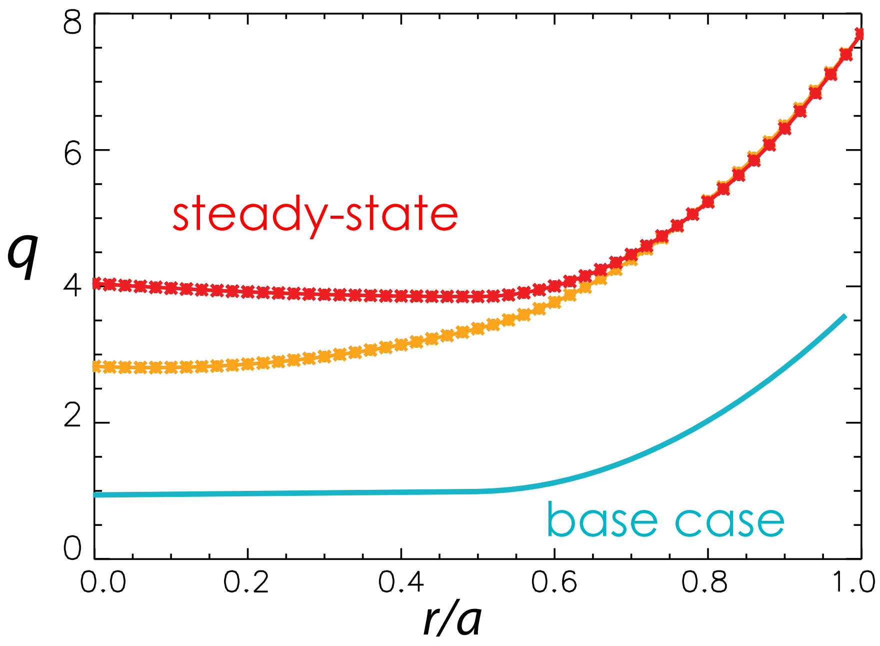


Low shear hurts both the steady-state and base cases.

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.



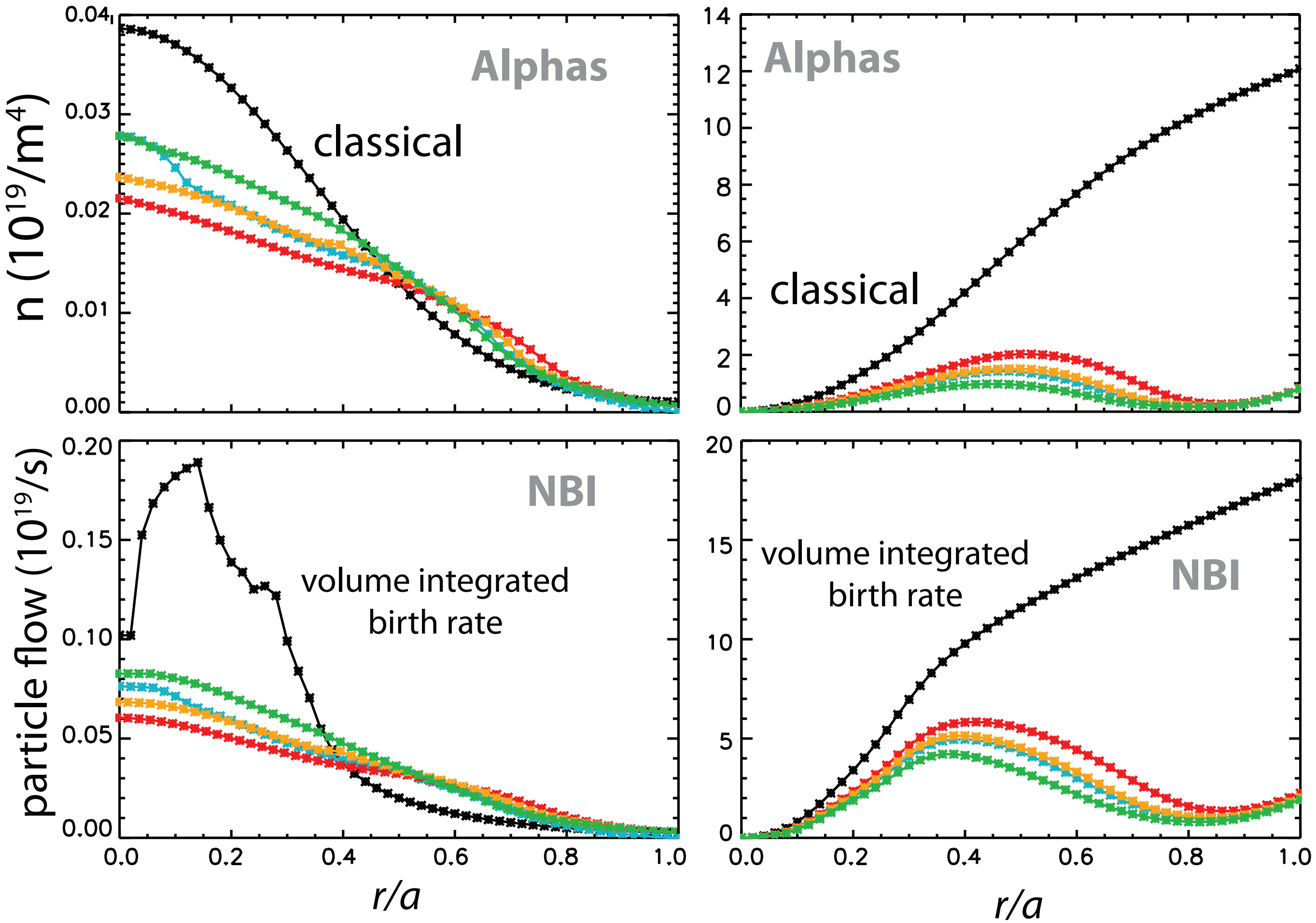


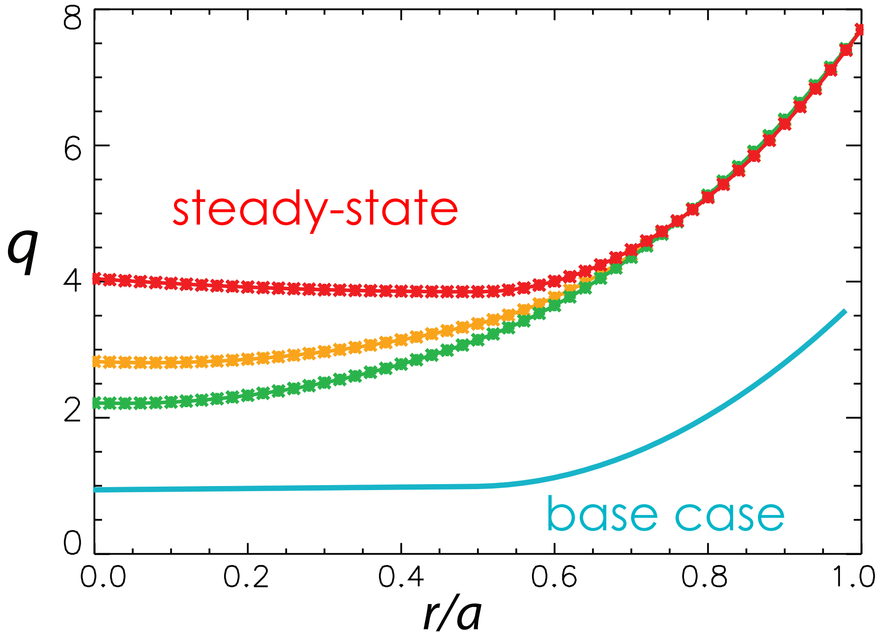
Low shear hurts both the steady-state and base cases.

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

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.



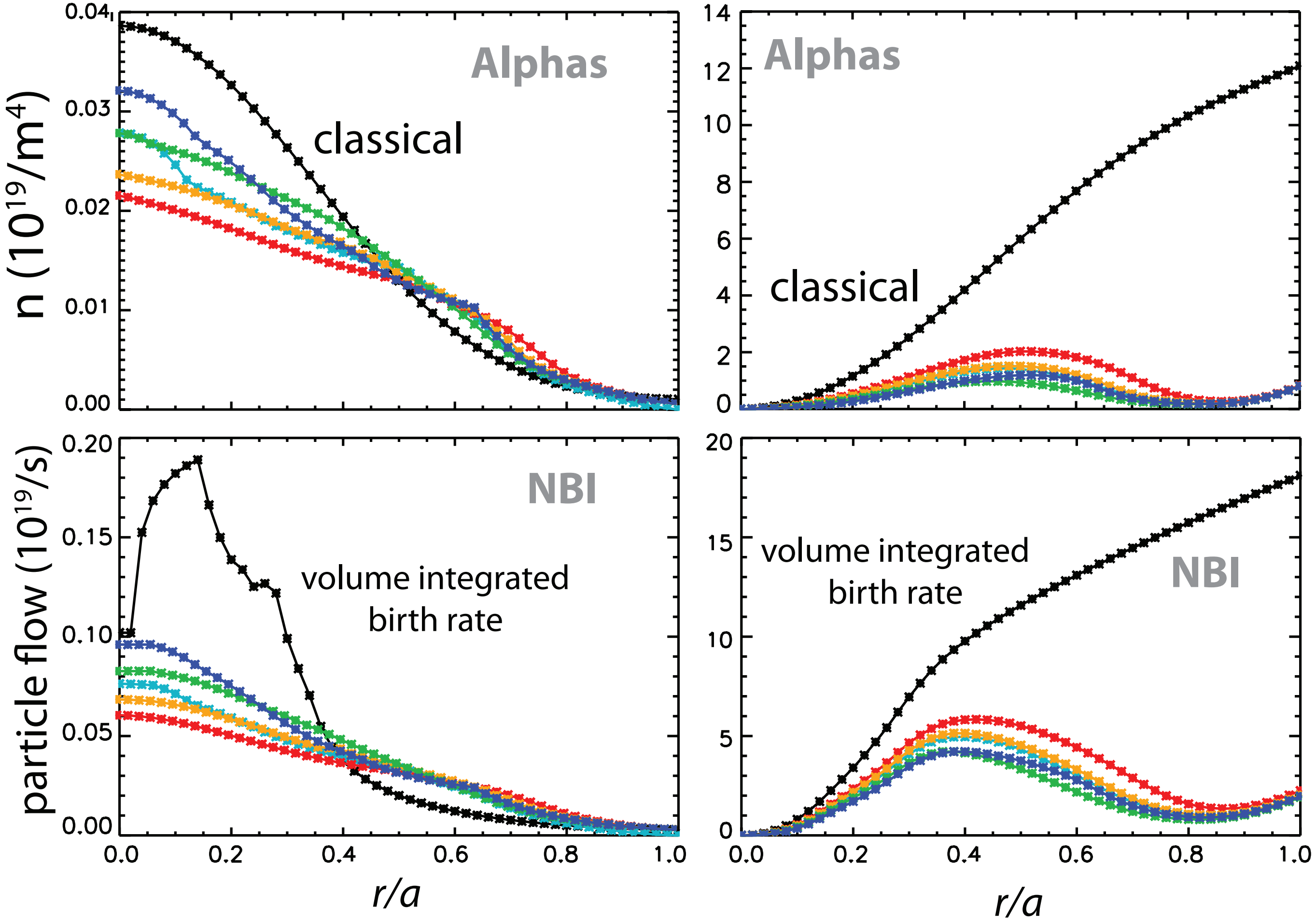


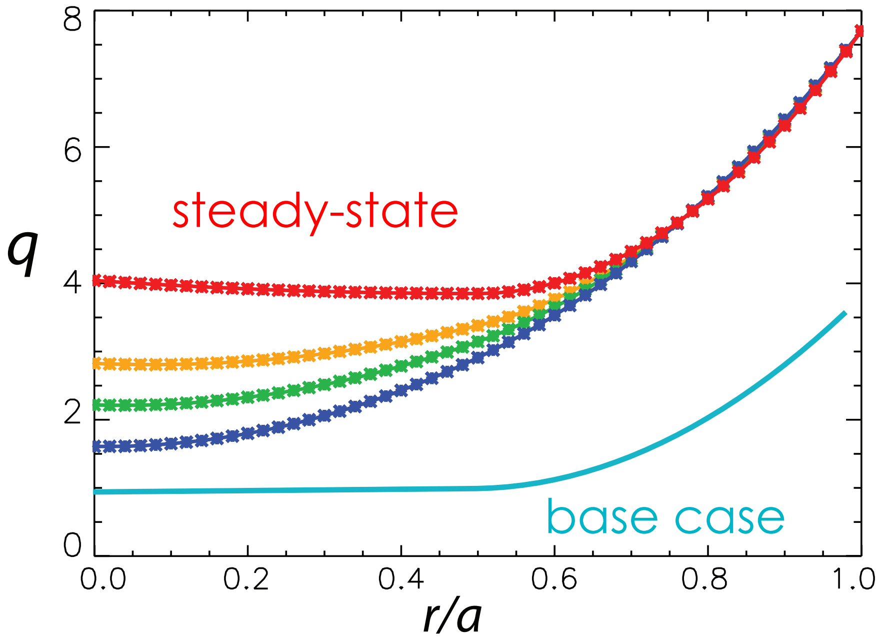
Low shear hurts both the steady-state and base cases.

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

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.



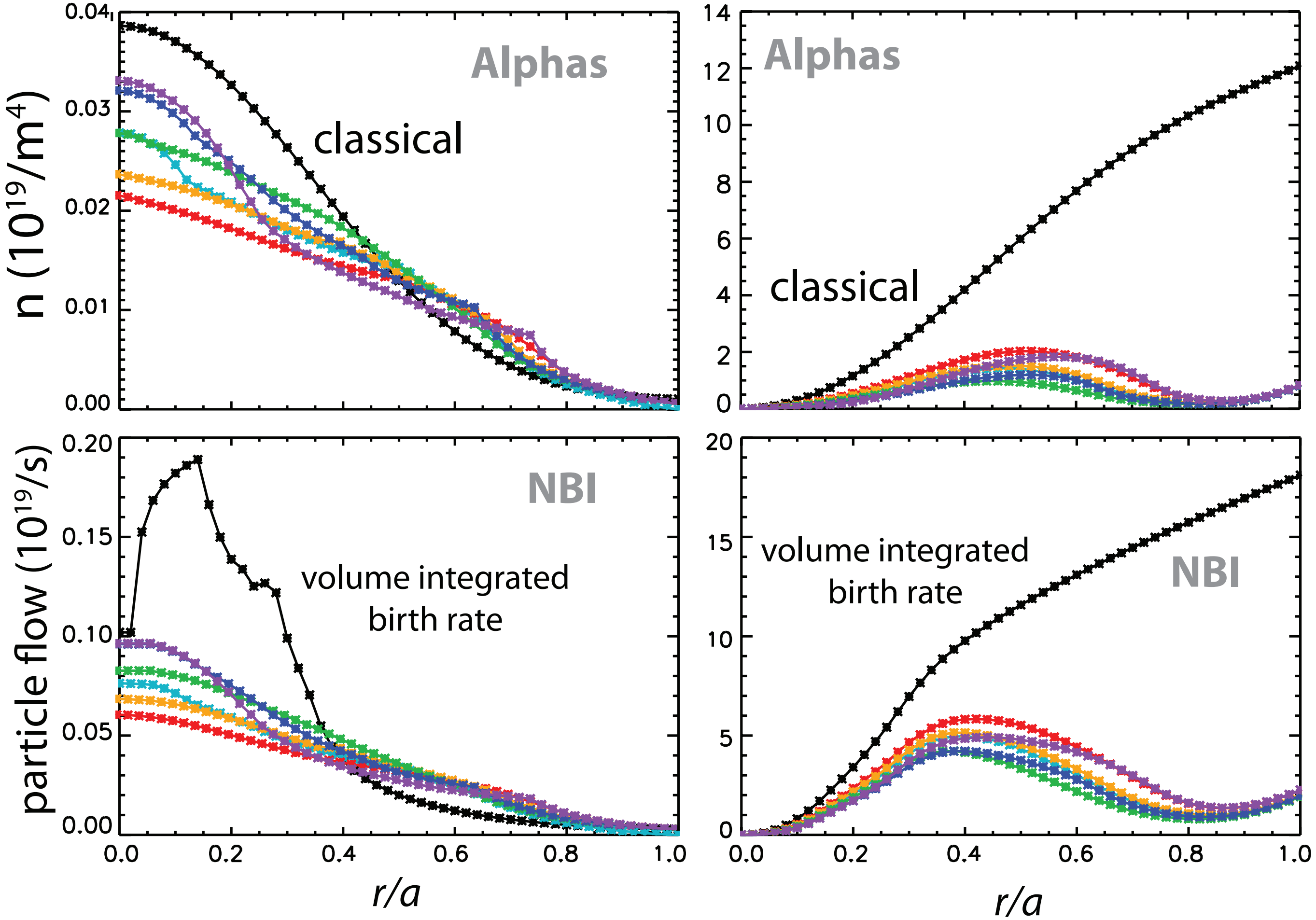


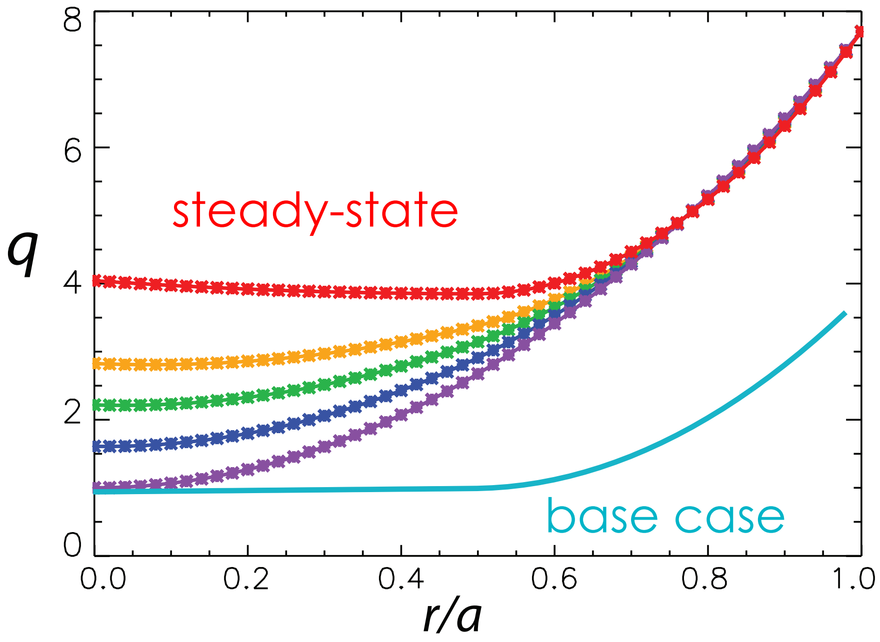
Low shear hurts both the steady-state and base cases.

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

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.

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

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

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.

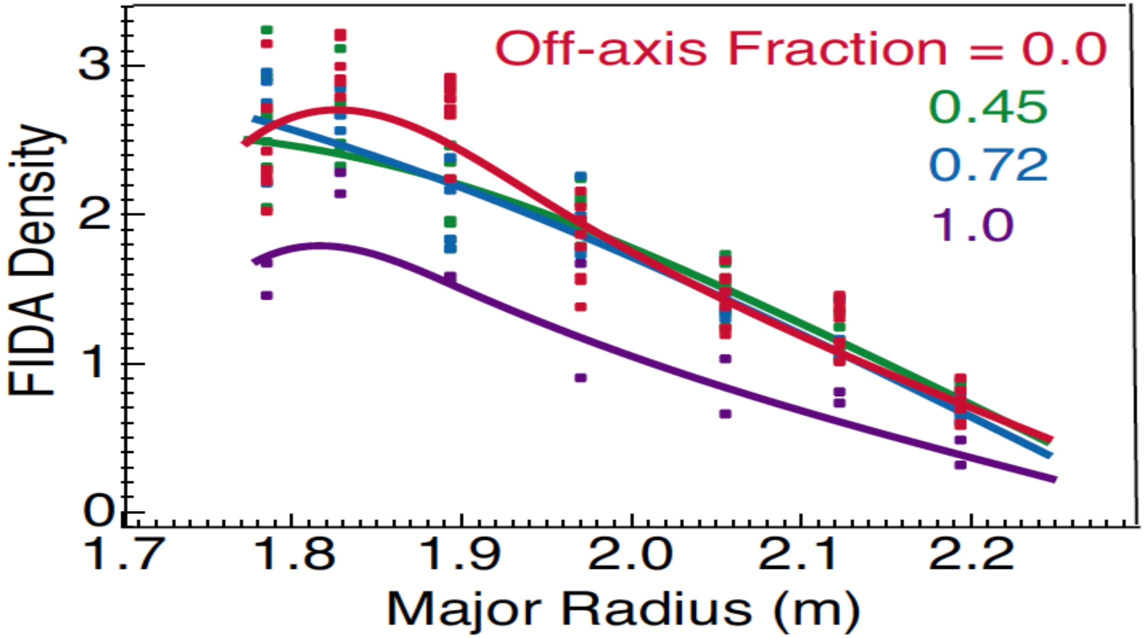
- Reductions in ITER current (increased q) or current penetration (increased q_{min} with lower core shear) increase mid-core confinement loss.

- 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:

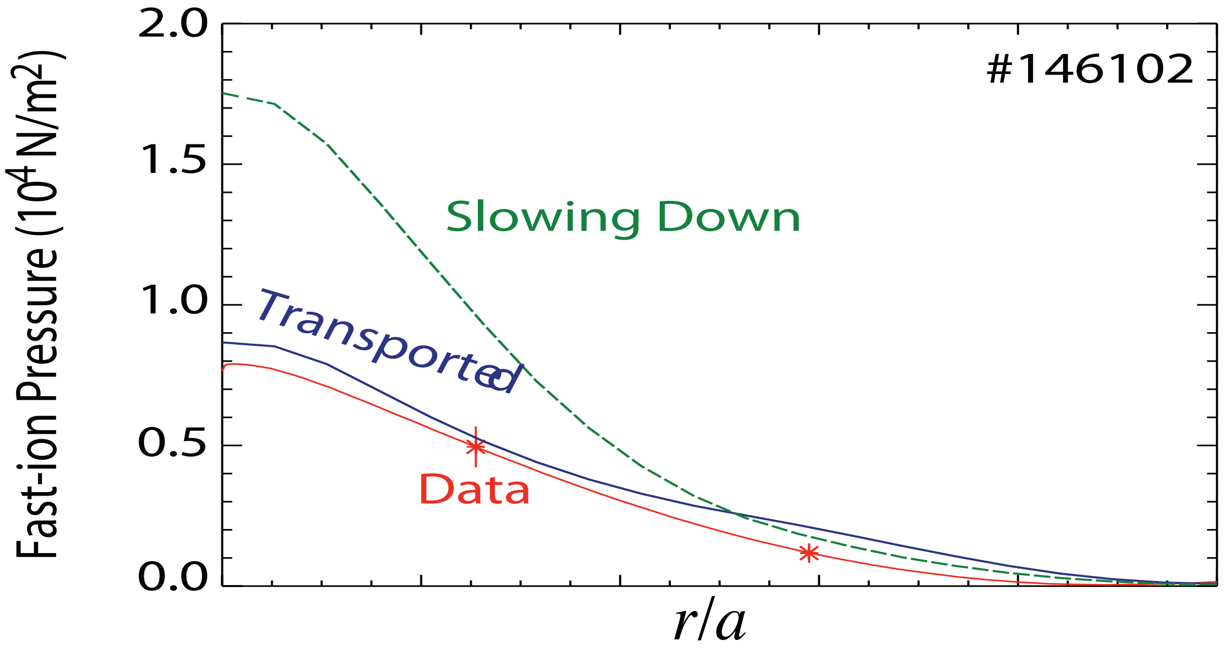
  - Estimation of **mode intermittency**, needed to predict peak heat flux (instead of time average)
  - Deploy **TGLFEP+ALPHA model into the AToM2** whole-device modeling project for use by broader community
  - Adjust inputs considering **broadened heating and current deposition profiles** in an integrated 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].

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

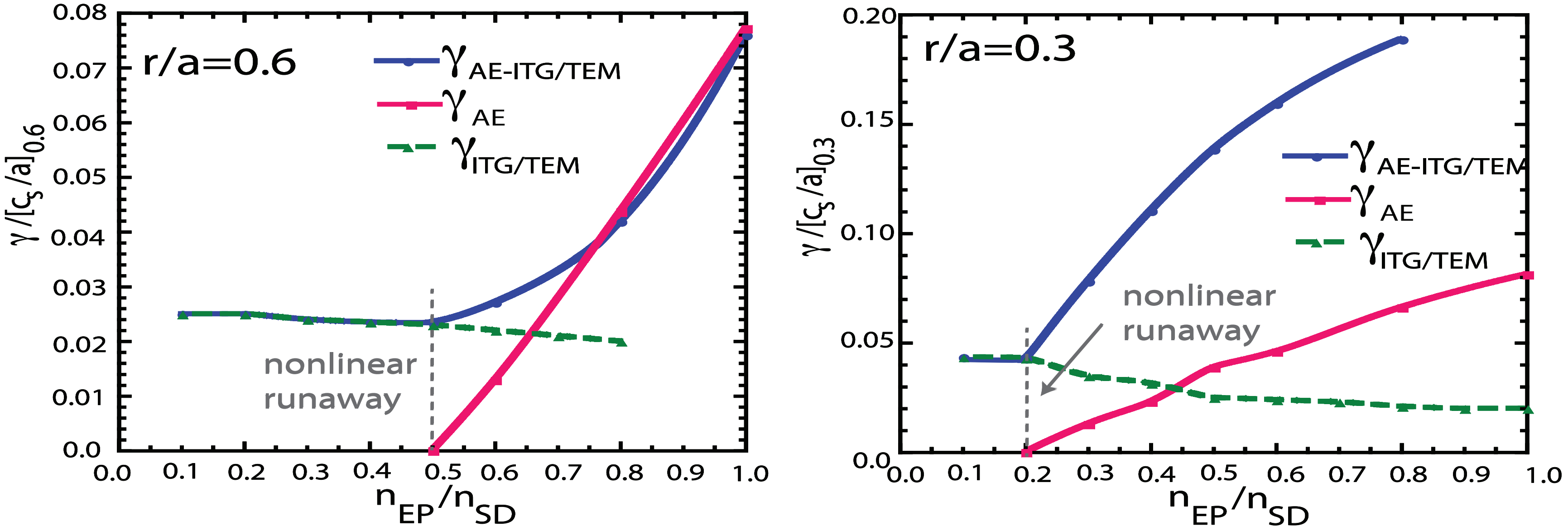
EP+thermal drive on AEs

γ_{AE}

only EP drive on AEs

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

leading microturbulent growth rate



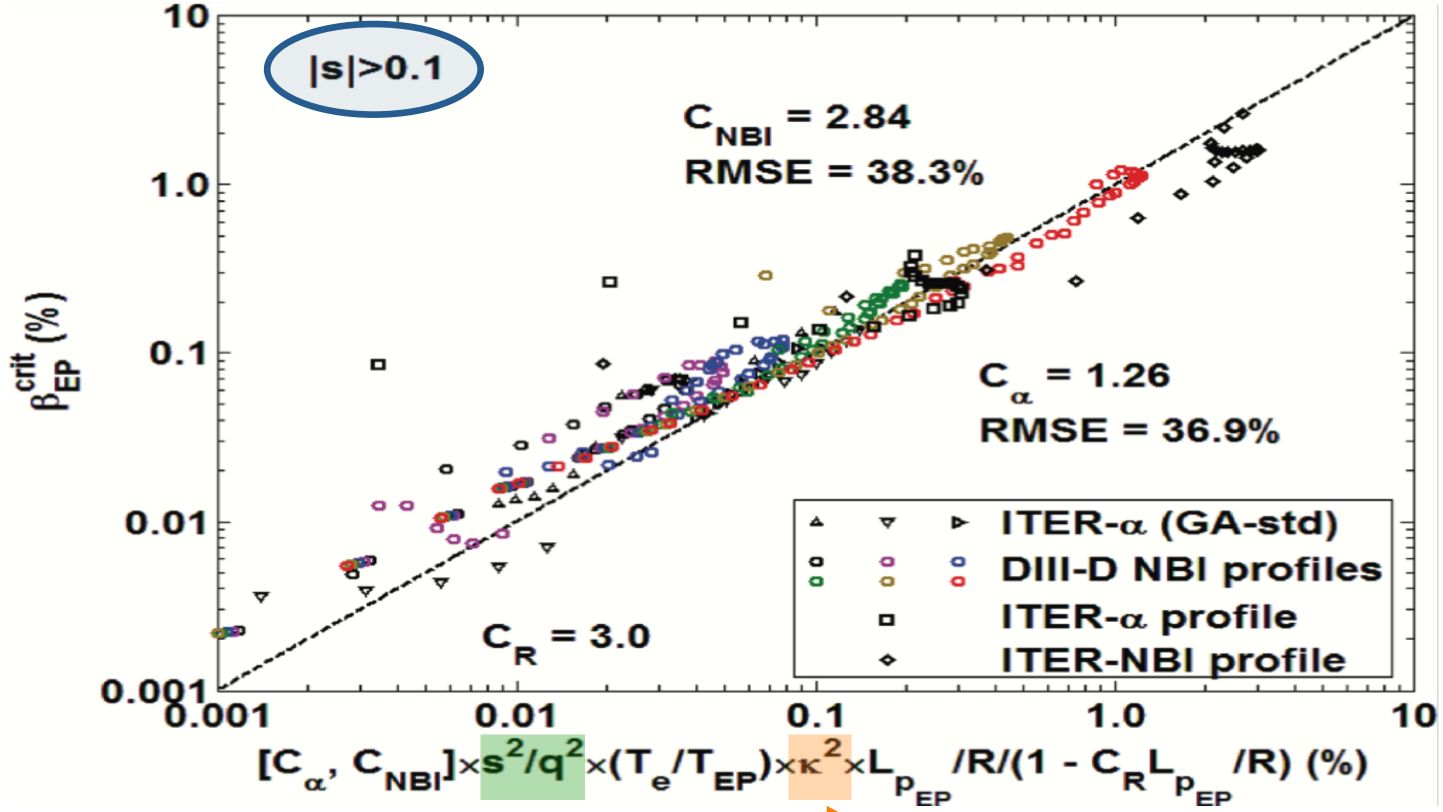
Runaway onset at $\gamma_{\mathrm{AE+ITG/TEM}}=\gamma_{\mathrm{ITG/TEM}}$ is due to suppression of AEs by microturbulence-driven zonal flows.

By luck, the **much simpler condition γ_{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)