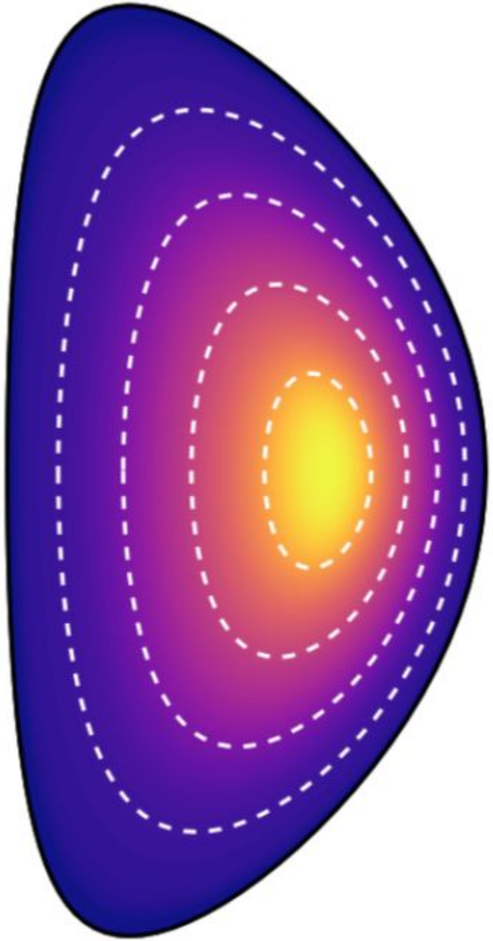
Characterization of Turbulence and Transport in a Tokamak Power Plant

Christopher Holland
University of California, San Diego

Presented at 2023 BOUT++ Workshop
Livermore, CA, January 9-12, 2023

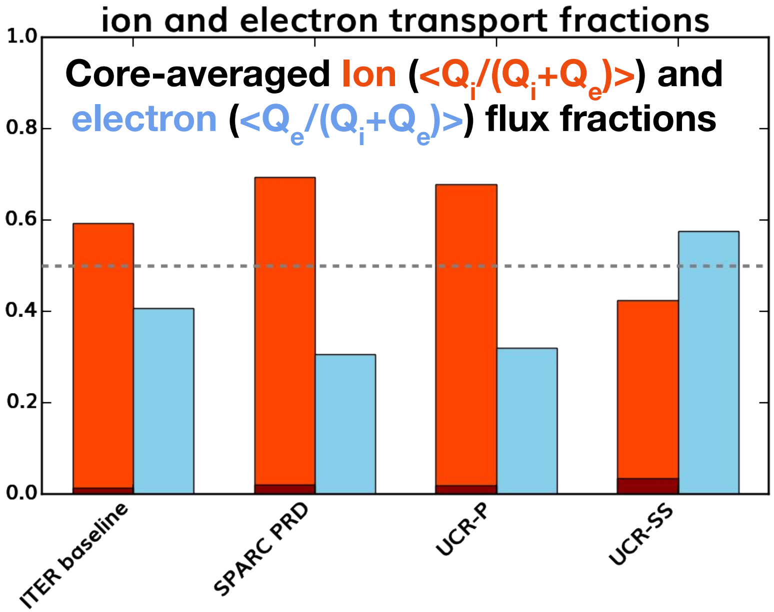


Basic considerations of reactor plasmas identify core transport and turbulence properties any viable D-T reactor must exhibit

- These requirements constrain what plasma parameters must be achieved for sustained performance required of a reactor

- More specifically, argue plasma core must:
  - Be both “collisionless” and well-coupled
  - Have majority of core thermal <u>and</u> particle transport driven by long-wavelength ITG/TEM turbulence

- Less clear what implications for near-edge/pedestal/SOL transport are, but set some interesting “boundary conditions”



Transport fractions for four burning plasma scenarios with dominant electron heating

Talk Outline

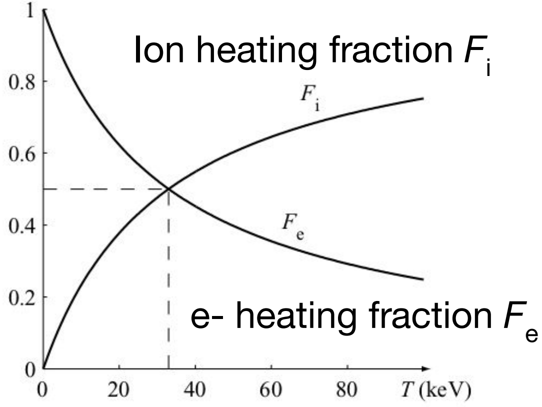
1. Sketch out basic picture of core transport in reactor
2. Using the fingerprint paradigm to constrain the processes consistent with this picture
3. Identifying and applying metrics to test this picture
4. Implications for near-edge and edge transport

Begin with a few basic assertions about necessary reactor plasma conditions and parameters

- The plasma must be strongly burning ($Q_{fusion} >> 1$) to both generate significant net electric power and avoid recirculating power costs
  - Therefore dominated by alpha heating rather than external sources
- At relevant temperatures, alphas predominantly heat electrons (roughly ⅔ to e-, ⅓ to ions)
  - Relevant: hot enough to fuse, cold enough to avoid stability limits, overwhelming radiation losses
- In order to efficiently sustain fusion reactions, a large fraction of this electron alpha heating must be transferred to ions to keep them hot
  - The plasma must therefore have low collisionality but be well-coupled

Begin with a few basic assertions about a reactor plasma, to be tested later

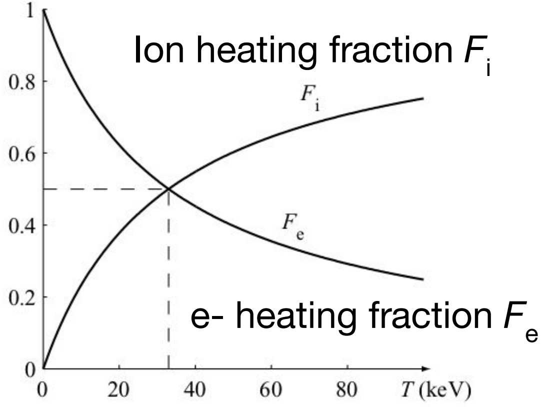
- The plasma must be strongly burning ($Q_{fusion} >> 1$) to both generate significant net electric power and avoid recirculating power costs
  - Therefore dominated by alpha heating rather than external sources
- At relevant temperatures, alphas predominantly heat electrons (roughly ⅔ to e-, ⅓ to ions)
  - Relevant: hot enough to fuse, cold enough to avoid stability limits, overwhelming radiation losses
- In order to efficiently sustain fusion reactions, a large fraction of this electron alpha heating must be transferred to ions to keep them hot
  - The plasma must therefore have low collisionality but be well-coupled



J. Freidberg, *Plasma Physics and Fusion Energy*, Fig. 9.12

Begin with a few basic assertions about a reactor plasma, to be tested later

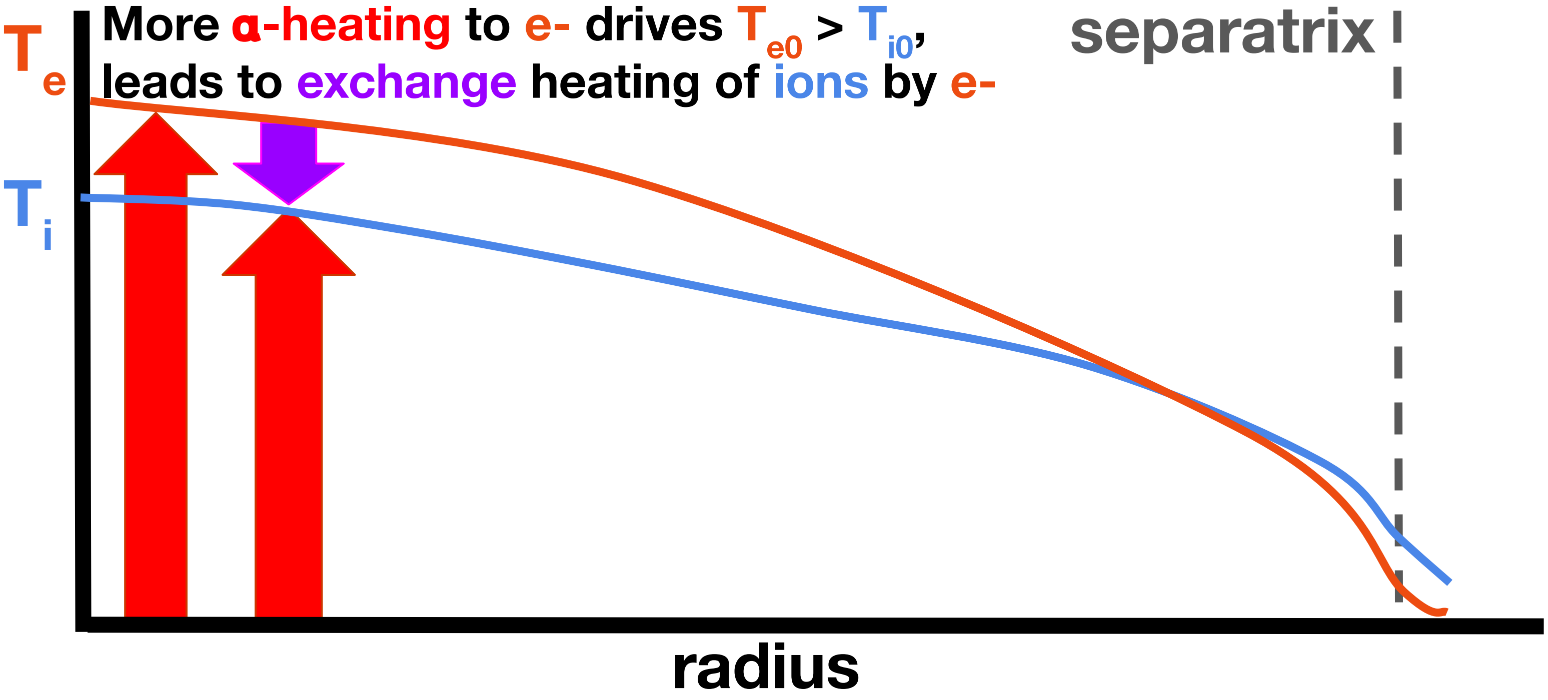
- The plasma must be strongly burning ($Q_{fusion} >> 1$) to both generate significant net electric power and avoid recirculating power costs
    - Therefore dominated by alpha heating rather than external sources
- At relevant temperatures, alphas predominantly heat electrons (roughly ⅔ to e-, ⅓ to ions)
    - Relevant: hot enough to fuse, cold enough to avoid stability limits, overwhelming radiation losses
- In order to efficiently sustain fusion reactions, a large fraction of this electron alpha heating must be transferred to ions to keep them hot
    - The plasma must therefore have low collisionality but be well-coupled



J. Freidberg, *Plasma Physics and Fusion Energy*, Fig. 9.12

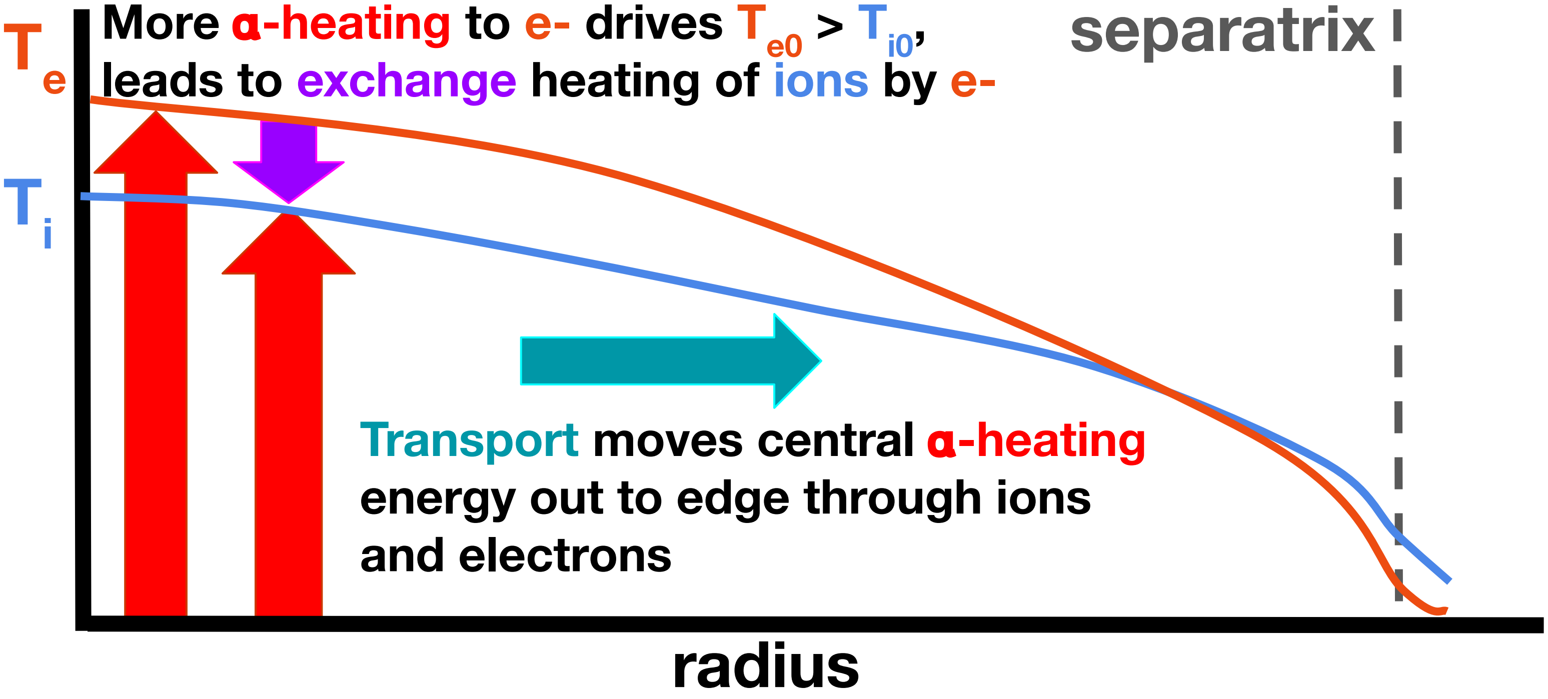
UC San Diego

Suggests a general picture of what transport in a viable fusion reactor must look like



More α-heating to e- drives $T_{e0} > T_{i0}$, leads to exchange heating of ions by e-

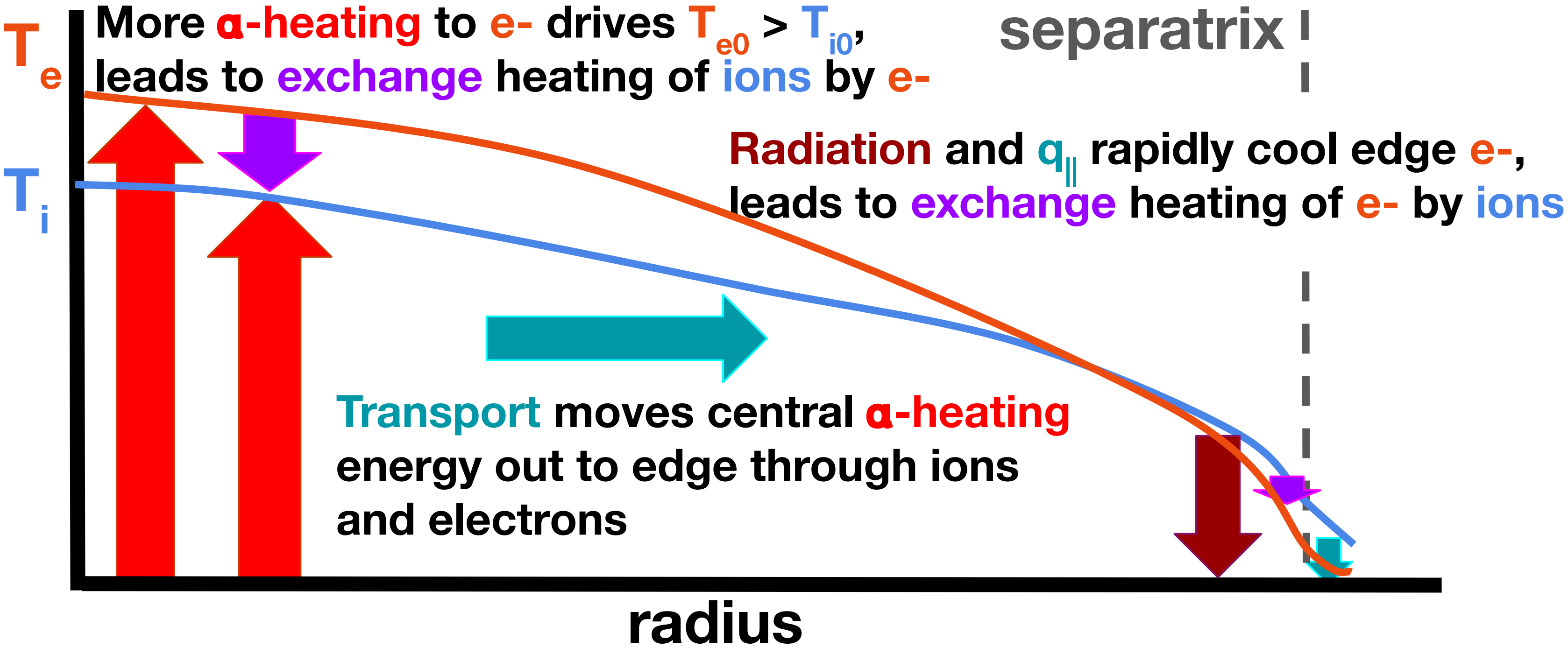
Suggests a general picture of what transport in a viable fusion reactor must look like



More α-heating to e- drives $T_{e0} > T_{i0}$, leads to exchange heating of ions by e-

Transport moves central α-heating energy out to edge through ions and electrons

Suggests a general picture of what transport in a viable fusion reactor must look like



More α-heating to e- drives $T_{e0} > T_{i0}$, leads to exchange heating of ions by e-

Radiation and $q_{||}$ rapidly cool edge e-, leads to exchange heating of e- by ions

Transport moves central α-heating energy out to edge through ions and electrons

Key point: reactor plasmas will have dominant electron heating but significant (likely dominant) core ion transport

- Once energy is “in” the core ions, cannot be lost there by radiation- must be transported out to edge

- (Assertion) In any viable reactor, ion collisionality (ν_i^*) will be small enough to make neoclassical transport negligible
  - $Q_{i,neo}/Q_{i,turb} \sim \chi_{i,neo}/\chi_{i,gB} \sim \rho_{i\theta}^2 \nu_{ii}/(\rho_i^2 v_{th}/R) \sim R\nu_{ii}/v_{th} \sim \nu_i^*$

- Therefore turbulent ion energy transport processes must play a key role in controlling core confinement

Key point: reactor plasmas will have dominant electron heating but significant (likely dominant) core ion transport

- Once energy is “in” the core ions, cannot be lost there by radiation- must be transported out to edge

- (Assertion) In any viable reactor, ion collisionality (ν_i^*) will be small enough to make neoclassical transport negligible
    - $Q_{i,neo}/Q_{i,turb} \sim \chi_{i,neo}/\chi_{i,gB} \sim \rho_{i\theta}^2 \nu_{ii}/(\rho_i^2 v_{th}/R) \sim R\nu_{ii}/v_{th} \sim \nu_i^*$

- Therefore turbulent ion energy transport processes must play a key role in controlling core confinement

Key point: reactor plasmas will have dominant electron heating but significant (likely dominant) core ion transport

- Once energy is “in” the core ions, cannot be lost there by radiation- must be transported out to edge

- (Assertion) In any viable reactor, ion collisionality (ν_i^*) will be small enough to make neoclassical transport negligible
    - $Q_{i,neo}/Q_{i,turb} \sim \chi_{i,neo}/\chi_{i,gB} \sim \rho_{i\theta}^2 \nu_{ii}/(\rho_i^2 v_{th}/R) \sim R\nu_{ii}/v_{th} \sim \nu_i^*$

- Therefore turbulent ion energy transport processes must play a key role in controlling core confinement

Key point: reactor plasmas will have dominant electron heating but significant (likely dominant) core ion transport

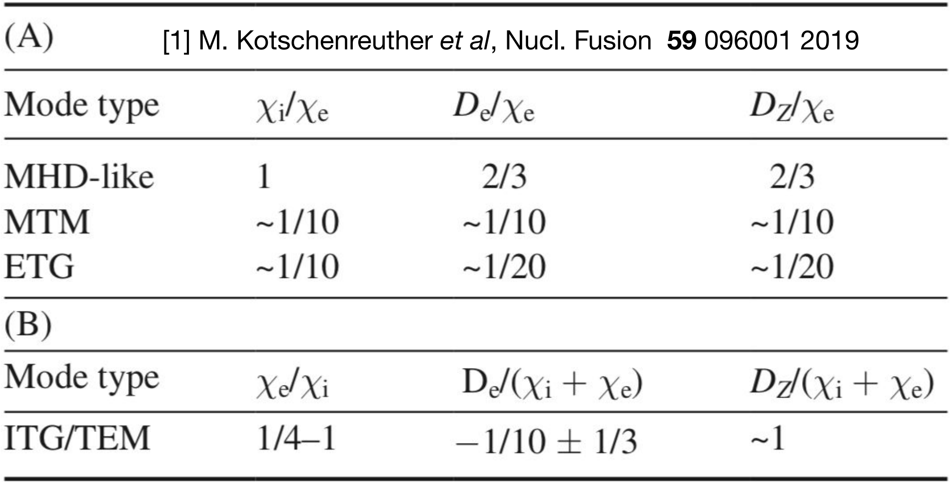
- Once energy is “in” the core ions, cannot be lost there by radiation- must be transported out to edge

- (Assertion) In any viable reactor, ion collisionality (ν_i^*) will be small enough to make neoclassical transport negligible
  - $Q_{i,neo}/Q_{i,turb} \sim \chi_{i,neo}/\chi_{i,gB} \sim \rho_{i\theta}^2\nu_{ii}/(\rho_i^2 v_{th}/R) \sim R\nu_{ii}/v_{th} \sim \nu_i^*$

- Therefore turbulent ion energy transport processes must play a key role in controlling core confinement

Viable reactor must have significant turbulent core ion heat flux; “fingerprint” paradigm [1] requires ITG/TEM

- **Neoclassical**: too small
  - Required by reactor ν_i^*
- **MTM, ETG**:
  - can be present, but can’t provide needed χ_i/χ_e
- **KBM/MHD-like modes**: only drive particle outflow, reactors very likely require core thermal particle pinch
  - Also want to avoid EP-driven modes: alpha redistribution, wall damage
- **Leaves only ITG (+TEM) as viable process**



[1] M. Kotschenreuther *et al*, Nucl. Fusion **59** 096001 2019

(A)

Mode type	χ_i/χ_e	D_e/χ_e	D_Z/χ_e
MHD-like	1	2/3	2/3
MTM	~1/10	~1/10	~1/10
ETG	~1/10	~1/20	~1/20

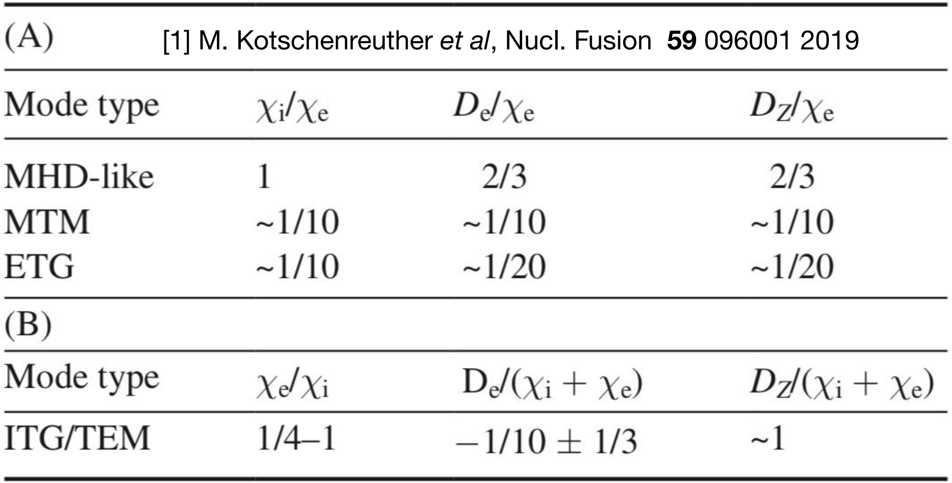
(B)

Mode type	χ_e/χ_i	$D_e/(\chi_i + \chi_e)$	$D_Z/(\chi_i + \chi_e)$
ITG/TEM	1/4–1	$-1/10 \pm 1/3$	~1

UC San Diego

Viable reactor must have significant turbulent core ion heat flux; “fingerprint” paradigm [1] requires ITG/TEM

- **Neoclassical**: too small
  - Required by reactor ν_i^*
- **MTM, ETG**:
  - can be present, but can’t provide needed χ_i/χ_e
- **KBM/MHD-like modes**: only drive particle outflow, reactors very likely require core thermal particle pinch
  - Also want to avoid EP-driven modes: alpha redistribution, wall damage
- **Leaves only ITG (+TEM) as viable process**



(A)

Mode type	χ_i/χ_e	D_e/χ_e	D_Z/χ_e
MHD-like	1	2/3	2/3
MTM	~1/10	~1/10	~1/10
ETG	~1/10	~1/20	~1/20

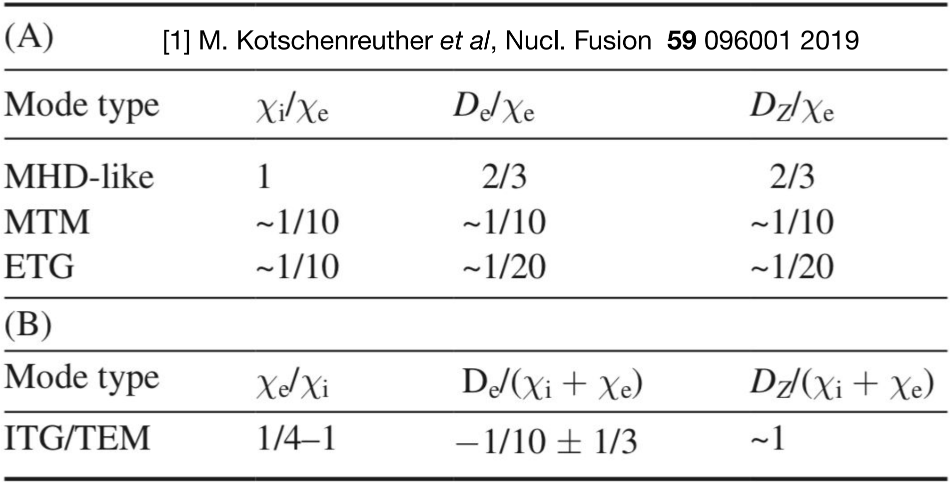
(B)

Mode type	χ_e/χ_i	$D_e/(\chi_i + \chi_e)$	$D_Z/(\chi_i + \chi_e)$
ITG/TEM	1/4–1	$-1/10 \pm 1/3$	~1

[1] M. Kotschenreuther *et al*, Nucl. Fusion **59** 096001 2019

Viable reactor must have significant turbulent core ion heat flux; “fingerprint” paradigm [1] requires ITG/TEM

- **Neoclassical**: too small
  - Required by reactor ν_i^*
- **MTM, ETG**:
  - can be present, but can’t provide needed χ_i/χ_e
- **KBM/MHD-like modes**: only drive particle outflow, reactors very likely require core thermal particle pinch
  - Also want to avoid EP-driven modes: alpha redistribution, wall damage
- **Leaves only ITG (+TEM) as viable process**



[1] M. Kotschenreuther *et al*, Nucl. Fusion **59** 096001 2019

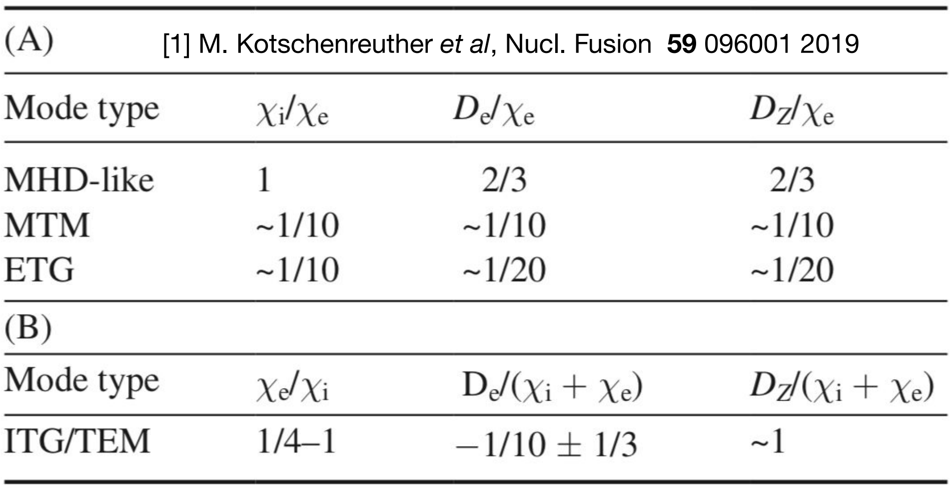
(A)

Mode type	χ_i/χ_e	D_e/χ_e	D_Z/χ_e
MHD-like	1	2/3	2/3
MTM	~1/10	~1/10	~1/10
ETG	~1/10	~1/20	~1/20

(B)

Mode type	χ_e/χ_i	$D_e/(\chi_i + \chi_e)$	$D_Z/(\chi_i + \chi_e)$
ITG/TEM	1/4–1	$-1/10 \pm 1/3$	~1

Viable reactor must have significant turbulent core ion heat flux; “fingerprint” paradigm [1] requires ITG/TEM



[1] M. Kotschenreuther *et al*, Nucl. Fusion **59** 096001 2019

(A)

Mode type	χ_i/χ_e	D_e/χ_e	D_Z/χ_e
MHD-like	1	2/3	2/3
MTM	~1/10	~1/10	~1/10
ETG	~1/10	~1/20	~1/20

(B)

Mode type	χ_e/χ_i	$D_e/(\chi_i + \chi_e)$	$D_Z/(\chi_i + \chi_e)$
ITG/TEM	1/4–1	$-1/10 \pm 1/3$	~1

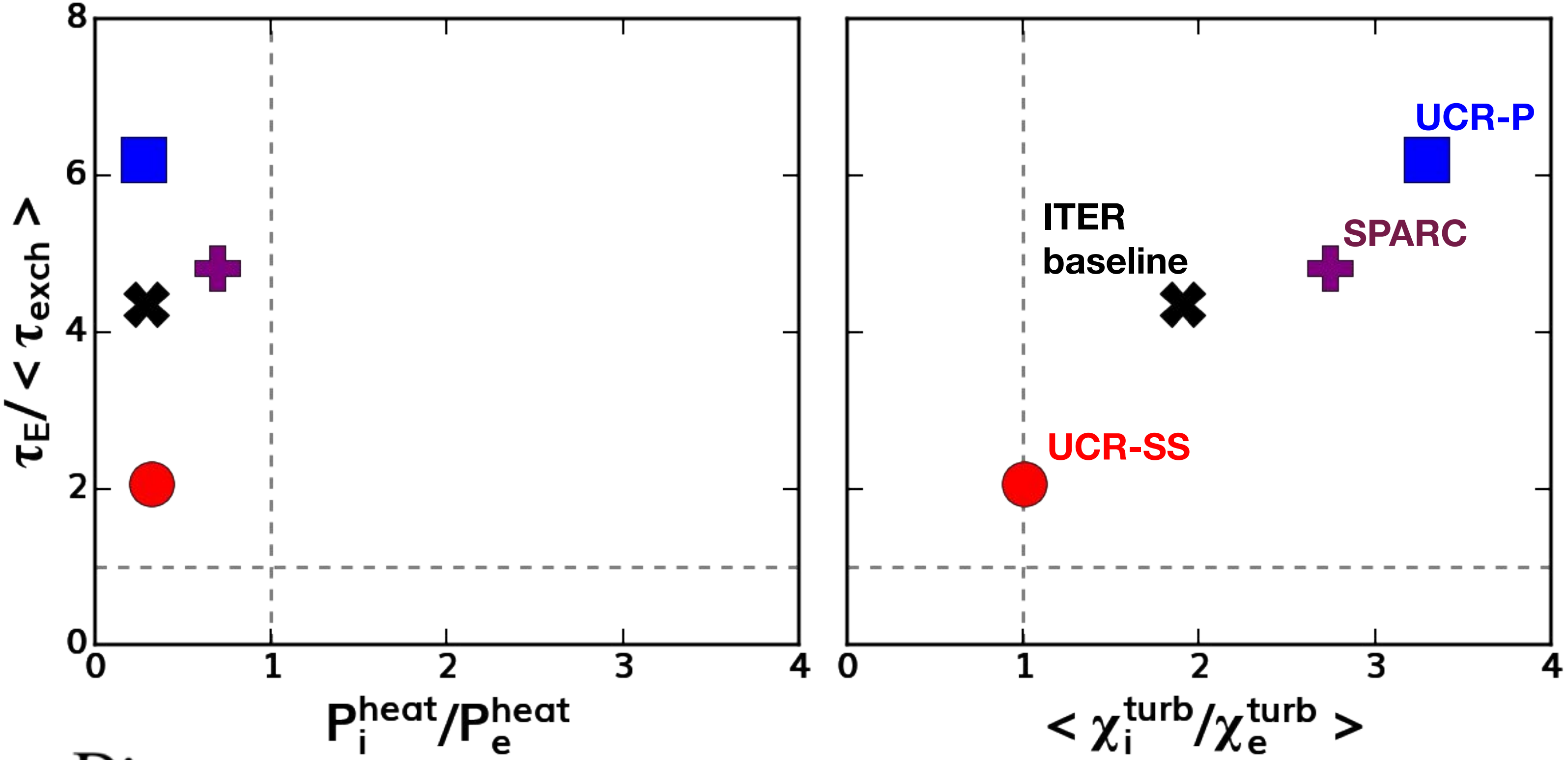
- **Neoclassical**: too small
    - Required by reactor ν_i^*
- **MTM, ETG**:
    - can be present, but can’t provide needed χ_i/χ_e
- **KBM/MHD-like modes**: only drive particle outflow, reactors very likely require core thermal particle pinch
    - Also want to avoid EP-driven modes: alpha redistribution, wall damage
- **Leaves only ITG (+TEM) as viable process**

Quantitative metrics can be formulated to further test and utilize heuristic picture presented

- Degree of core coupling can be determined by examining ratio of energy confinement and exchange times τ_E/τ_{exch}
    - $\tau_E >> \tau_{exch}$: energy confined long enough to equilibrate
    - $\tau_E << \tau_{exch}$: energy leaves system before equilibration

- Core-averaged $<\chi_i^{turb}/\chi_e^{turb}>$ can be used to fingerprint the dominant core transport mechanisms
    - Need to remove any neoclassical contributions to catch the right suspect(s)

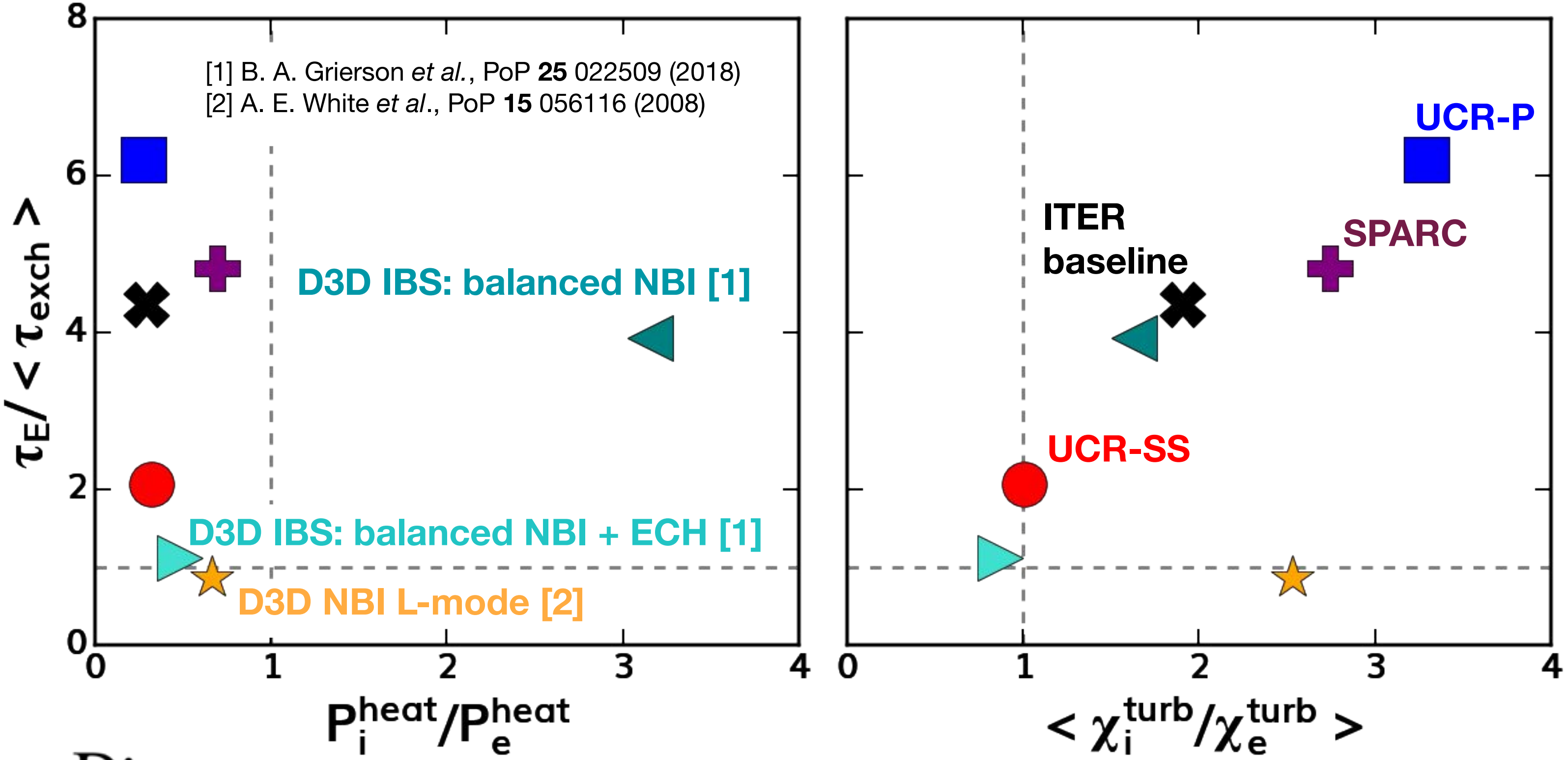
All four burning plasmas are well-coupled, and have $\chi_i^{turb}/\chi_e^{turb} \gtrsim 1$ consistent with ITG/TEM dominance



UC San Diego

Holland/BOUT++/2023

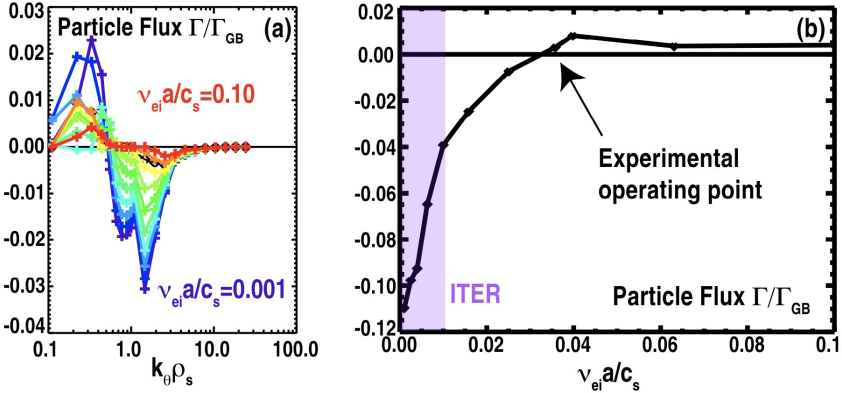
These metrics allow comparison of current-day plasmas to future conditions



[1] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[2] A. E. White *et al*., PoP **15** 056116 (2008)

Some quick thoughts on pros and cons of these conclusions for core modeling

- Pros:
  - ITG is our most well-studied mode, should have the highest confidence in projecting it to future regimes
  - Expect ITG/TEM-driven main-ion peaking to increase with lower collisionality [1,2,3]
  - Expect weaker core high-Z impurity accumulation [4]
- Cons:
  - EM effects can weaken pinch [3]
  - Too much peaking can push into β limits



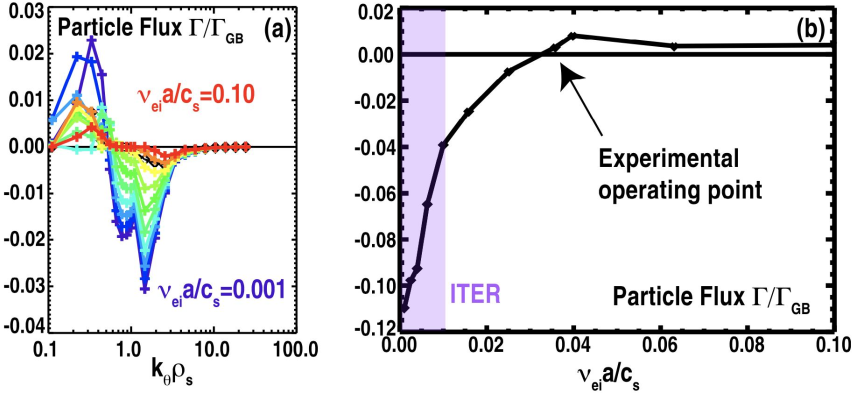
TGLF-predicted turbulent particle flux spectra and scaling [2]

[1] C. Angioni *et al.*, PPCF **51** 124017 (2009)
[2] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[3] E. Fable *et al.*, Nucl. Fusion **59** 076042 (2019)
[4] C. Angioni PPCF **63** 073001 (2021)

UC San Diego

Some quick thoughts on pros and cons of these conclusions for core modeling

- Pros:
  - ITG is our most well-studied mode, should have the highest confidence in projecting it to future regimes
  - Expect ITG/TEM-driven main-ion peaking to increase with lower collisionality [1,2,3]
  - Expect weaker core high-Z impurity accumulation [4]
- Cons:
  - EM effects can weaken pinch [3]
  - Too much peaking can push into β limits



TGLF-predicted turbulent particle flux spectra and scaling [2]

[1] C. Angioni *et al.*, PPCF **51** 124017 (2009)
[2] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[3] E. Fable *et al.*, Nucl. Fusion **59** 076042 (2019)
[4] C. Angioni PPCF **63** 073001 (2021)

So what does this picture mean for near-edge and edge transport? (Trying to be more general than only pedestals)

- First, would assert this picture specifies an effective inner boundary condition for this region- need to get plasma as hot and dense as sustainably possible inside separatrix
  - Core transport stiffness + minimal reactor core actuators requires this

- Second, what will be the impact of low ion collisionality and large ion energy flux at core/near-edge boundary?
  - Along with small ρ^*, will push to stronger ITG/TEM at “top” of region, weaker neoclassical transport
  - How far through the region will these modes remain important (if at all)?
    Will depend on parameters like separatrix collisionality (and thus SOL transport, attached/detached conditions, radiative impurities, etc.)...
  - How will they interact with KBM/PBM/MHD- large busty ELMS, quiescent steady state,...?

The tight coupling of particle transport and ion transport mechanisms will be essential

- Typically in current-day devices, inter-ELM density profile set by balance of fueling (core & edge) and resistive/fluid transport mechanisms (neoclassical, RBM, KBM etc.)

- In a burning plasma, will need sufficiently hot & dense plasma at “top” of near-edge region that both of those mechanisms will be quite weak there

- How will a change in balance of transport drivers and fueling impact density near-edge profile? Will we still have classic pedestal structure, or something broader?
  - Changes may not necessarily be bad, but shouldn’t assume future devices will look like what study/assume now
  - As Pat said this morning, essential to do some cost-benefit analysis

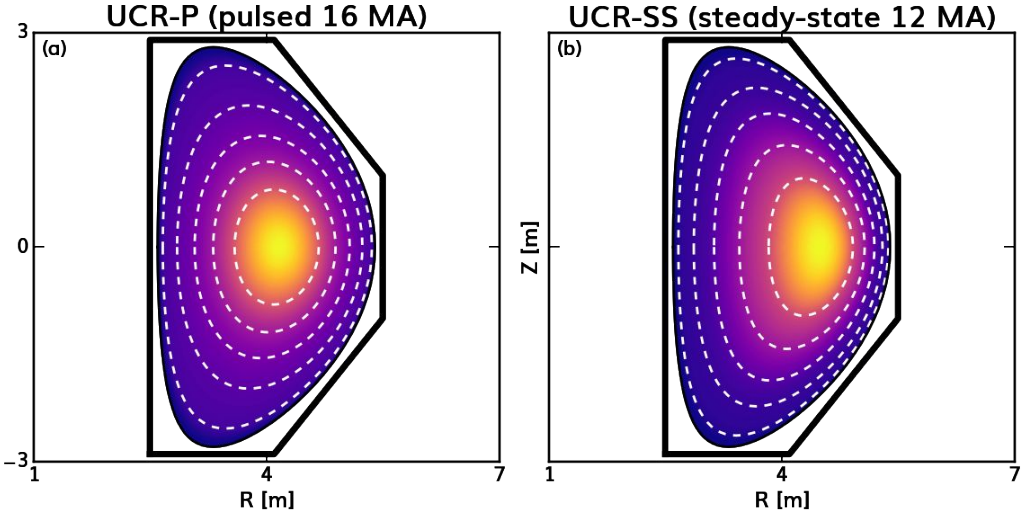
Backups

UCR (**<u>Unoptimized</u>** **C**ompact **R**eactor) size, shape, and field drawn from values used in similar studies

- **B_0 = 8 T, R = 4 m, a = 1.4 m, κ = 2, δ=0.5**
  - B_{coil} ~22 T depending on inboard build

- **UCR-P** = **Pulsed**
  - **I_p = 16 MA -> q_{95} ~ 5**
  - **n_{ped} = 2.0e20 m^{-3}** (~0.77 n_G)

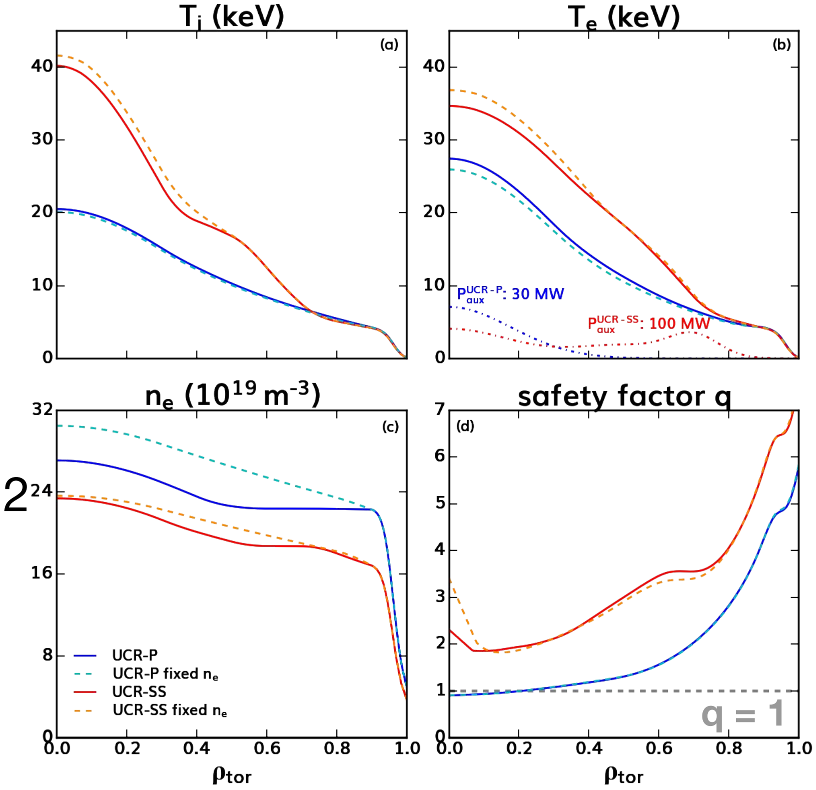
- **UCR-SS** = Steady **State**
  - **I_p = 12 MA -> q_{95} ~ 6.5**
  - **n_{ped} = 1.5e20 m^{-3}** (~0.77 n_G)



Most plots drawn from C. Holland *et al*, "**Development of Compact Tokamak Fusion Reactor Use Cases to Inform Future Transport Studies**", submitted to Journal of Plasma Physics

STEP workflow yields inductive and steady-state scenarios that can meet specified 200+ MWe goal

- **UCR-P**: **P_{net} ~ 218 MWe**
  - P_{aux} = 30 MW, Q_{fus} ~ 27, β_N = 1.7
  - **q_{95} = 4.7**, f_{BS} = 0.27, **n/n_G = 0.90**
  - Sawtooth inversion r_{tor} = 0.3
- **UCR-SS**: **P_{net} ~ 219 MWe**
  - P_{aux} = 100 MW, Q_{fus} ~ 12.9, β_N = 3.2
  - q_{95} = 6.5, **f_{BS} = 0.57, n/n_G = 1.02**
  - Requires conformal wall for *n* = 1 stability; higher *n* still TBD

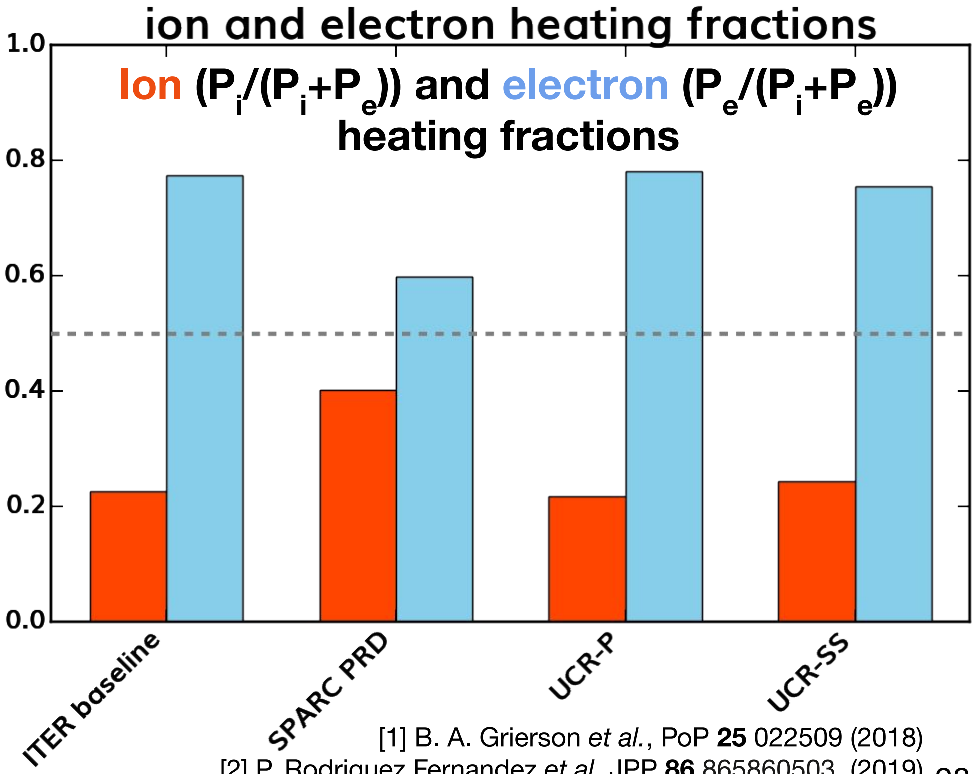


Holland/BOUT++/2023

To more quantitatively test this picture, examine how well it describes four different burning plasmas

Examine this picture using:

- ITER baseline (15 MA) scenario [1]
    - Added tungsten fraction with n_W/n_e = 1.5e-5 (Z_{avg} = 50) for consistency with other cases
- SPARC primary reference discharge (PRD) [2]
- Use case reactor (UCR) [3]
    - R_0 = 4 m, B_0 = 8 T tokamak producing ~1 GW fusion power
    - **UCR-P**: 16 MA pulsed
    - **UCR-SS**: 12 MA steady-state
    - See APS22 poster for more details



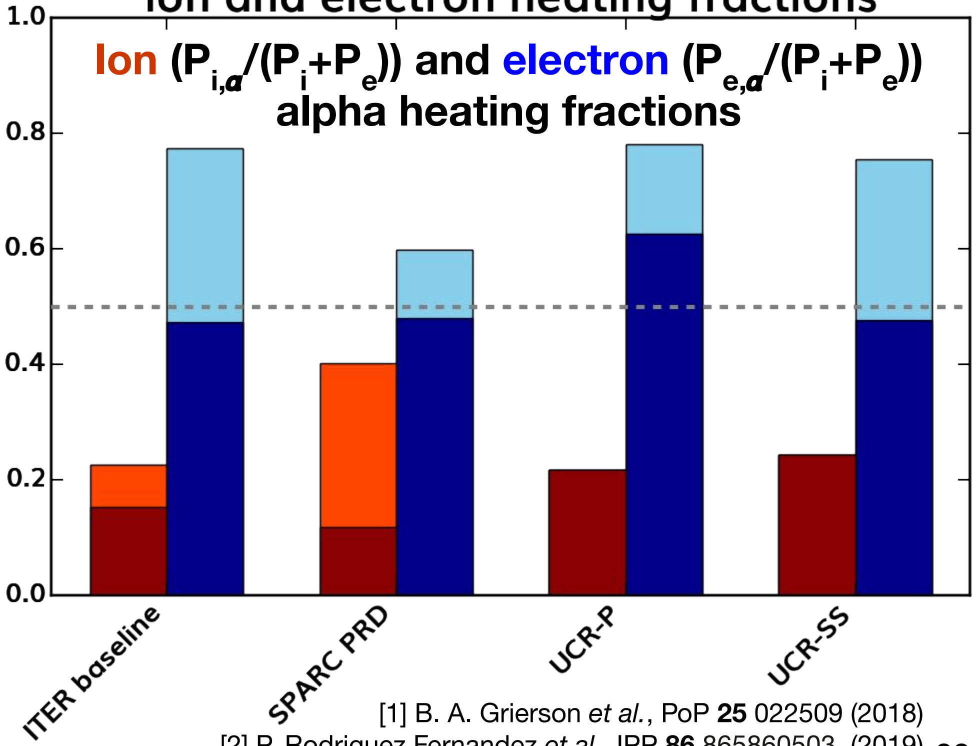
[1] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[2] P. Rodriguez Fernandez *et al*, JPP **86** 865860503 (2019)
[3] C. Holland *et al*, submitted to JPP (2022)

In all four scenarios (including UCR steady-state) α-heating dominates and is predominantly to electrons

Examine this picture using:

- ITER baseline (15 MA) scenario [1]
    - Added tungsten fraction with n_W/n_e = 1.5e-5 (Z_{avg} = 50) for consistency with other cases
- SPARC primary reference discharge (PRD) [2]
- Use case reactor (UCR) [3]
    - R_0 = 4 m, B_0 = 8 T tokamak producing ~1 GW fusion power
    - **UCR-P**: 16 MA pulsed
    - **UCR-SS**: 12 MA steady-state
    - See my poster this PM for more details

ion and electron heating fractions

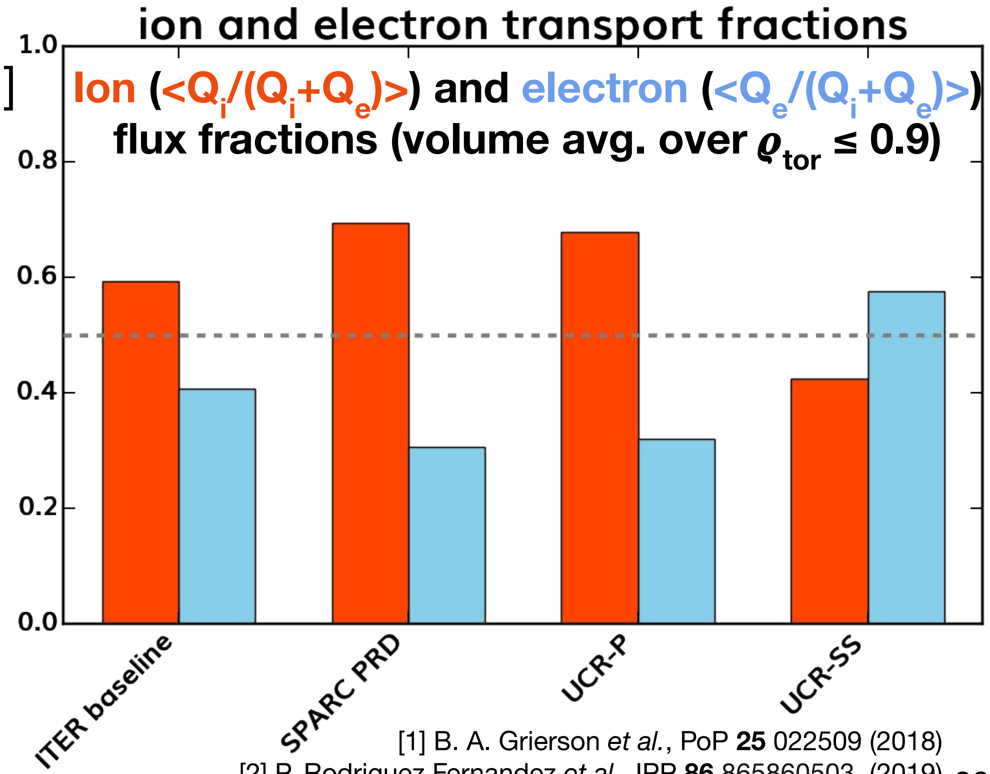


[1] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[2] P. Rodriguez Fernandez *et al*, JPP **86** 865860503 (2019)
[3] C. Holland *et al*, submitted to JPP (2022)

All three inductive burning plasmas have > 50% core transport through ions (UCR-SS ~ 40%)

Examine this picture using:

- ITER baseline (15 MA) scenario [1]
  - Added tungsten fraction with n_W/n_e = 1.5e-5 (Z_{avg} = 50) for consistency with other cases
- SPARC primary reference discharge (PRD) [2]
- Use case reactor (UCR) [3]
  - R_0 = 4 m, B_0 = 8 T tokamak producing ~1 GW fusion power
  - **UCR-P**: 16 MA pulsed
  - **UCR-SS**: 12 MA steady-state
  - See my poster this PM for more details



Holland/BOUT++/2023

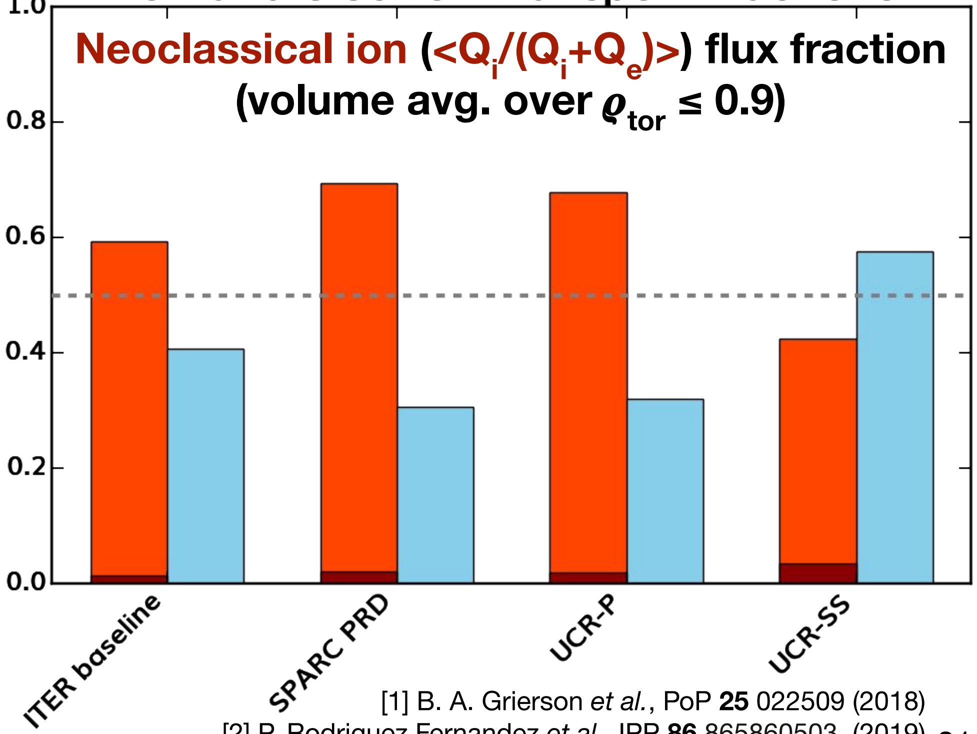
[1] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[2] P. Rodriguez Fernandez *et al*, JPP **86** 865860503 (2019)
[3] C. Holland *et al*, submitted to JPP (2022)

Neoclassical energy transport negligible in all four burning plasmas

Examine this picture using:

- ITER baseline (15 MA) scenario [1]
  - Added tungsten fraction with n_W/n_e = 1.5e-5 (Z_{avg} = 50) for consistency with other cases
- SPARC primary reference discharge (PRD) [2]
- Use case reactor (UCR) [3]
  - R_0 = 4 m, B_0 = 8 T tokamak producing ~1 GW fusion power
  - **UCR-P**: 16 MA pulsed
  - **UCR-SS**: 12 MA steady-state
  - See my poster this PM for more details

ion and electron transport fractions



UC San Diego

Holland/BOUT++/2023

[1] B. A. Grierson *et al.*, PoP **25** 022509 (2018)
[2] P. Rodriguez Fernandez *et al*, JPP **86** 865860503 (2019)
[3] C. Holland *et al*, submitted to JPP (2022)