Turbulent transport avoids core particle depletion in stellarators

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Overview

1. Introduction
    - The stellarator: candidate concept for fusion reactors
    - Importance of neoclassical and turbulent transport
    - Modeling turbulent transport with `stella`
2. Motivation for the study of the effect of turbulence on stellarator particle transport
3. Neoclassical particle transport
4. Turbulent particle transport
    - Turbulence can drive inwards convection
    - Dependence on $a/L_n, a/L_{T_i}, a/L_{T_e}$ and T_e/T_i
    - Dependence on the magnetic geometry
    - Correlation of sgn(Γ_s^{turb}) with the phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$
5. Analysis of ECRH discharge in W7-X
6. Conclusions and prospects

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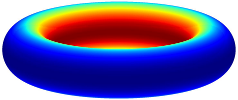
The stellarator: candidate concept for fusion reactors

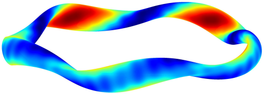
Tokamak

- Good confinement thanks to axisymmetry
- Part of $\mathbf{B}$ generated by a large current in the plasma
  - $\Rightarrow$ Current-driven instabilities
  - $\Rightarrow$ Difficult steady-state operation



Stellarator

- Entire $\mathbf{B}$ generated by external coils
  - $\Rightarrow$ No current-driven instabilities
  - $\Rightarrow$ Intrinsically steady-state operation
- Advantages come at a cost: 3D geometry
- Avoid intolerably large neoclassical transport
  - $\Rightarrow$ Tailoring of $\mathbf{B}$ needed to achieve good confinement
  - $\Rightarrow$ Stellarator optimization



Importance of neoclassical and turbulent transport (low collisionality)

	Physical origin	**Relevance in tokamaks**	**Relevance in stellarators**
Classical transport	Collisions	Typically negligible	Typically negligible
Neoclassical transport	Inhomogeneity of $\mathbf{B}$ $+$ Collisions	Small	Large in non-optimized stellarators
Turbulent transport	Collective fluctuations	Dominant	Relevant in neoclassically optimized stellarators

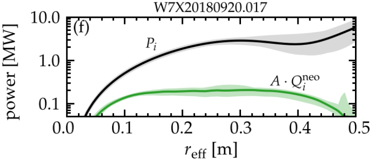
Importance of neoclassical and turbulent transport in Wendelstein 7-X

Neoclassical optimization

- W7-X is the first large stellarator designed for optimized neoclassical transport
- Neoclassical optimization experimentally demonstrated [Beidler, 2021]

Relevance of turbulent transport in W7-X

- Most discharges: neocl. transport cannot account for the total heat losses [Bozhenkov, 2020]
- Gap between the input power (black) and neoclassical losses (green) of a factor 10
- Gap is expected to be due to turbulence



Neoclassical and turbulent models are required to understand transport

- Neoclassical simulations are a mature field and have been routinely used for decades
- Turbulent simulations in stellarator plasmas are much less mature. However, recent developments in theory, release of new gyrokinetic codes and increased supercomputing capabilities now allow to address the problem of turbulent transport in stellarators
- Turbulent particle transport in tokamaks is much better understood [Angioni, 2009], e.g., thermo-diffusion [Coppi, 1978], curvature pinch [Weiland, 1989], ...

Modeling turbulent transport with `stella`

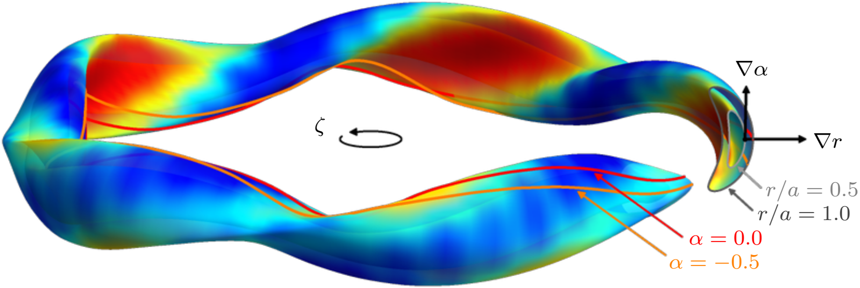
Gyrokinetic code `stella`

- Operator-split, implicit-explicit time advance scheme to maximize the allowable time step size [Barnes, 2019]
- In this work: electrostatic, flux-tube, ion-scales, kinetic ions and electrons

Coordinate system used in `stella`

- Coordinate along magnetic field lines ζ
- Flux surface label r
- Field line label α

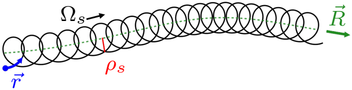
Magnetic equilibrium of Wendelstein 7-X (minor radius a)



Modeling turbulent transport with `stella`

Kinetic (electrostatic) description

- Distribution function $f_s(\vec{r},\vec{v},t)$ and electrostatic fluctuation φ
- Vlasov equation coupled to the quasi-neutrality condition



Electrostatic δf gyrokinetic description [Catto, 1978; Parra 2011]

- Assume the plasma is strongly magnetized $(\rho_s \ll a)$
- Turbulent fluctuations occur at Larmor radius scales $(k_\perp \rho_s \sim 1)$
- Fluctuation frequency is much smaller than the cyclotron frequency $(\omega \ll \Omega_s)$
- Turbulence is elongated along field lines, short perpendicular spatial scales $(k_\parallel \ll k_\perp)$

Gyrokinetic ordering: $$\frac{\delta f_s}{f_s} \sim \frac{q_s\varphi}{T_s} \sim \frac{k_\parallel}{k_\perp} \sim \frac{\omega}{\Omega_s} \sim \frac{\rho_s}{a} \ll 1$$

- Average out the fast gyro-motion, to eliminate the gyro-angle ⇒ kinetics of charged rings

Modeling turbulent transport with `stella`

Flux tube approach

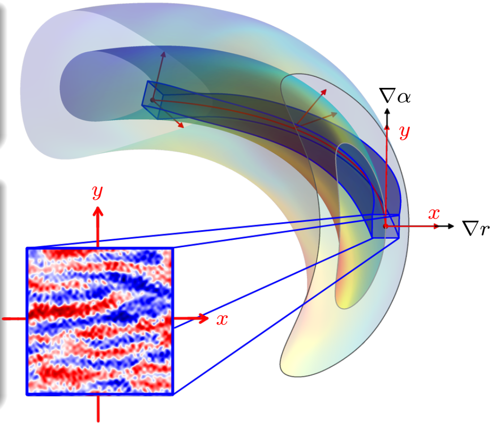
- Turbulent fluctuations are elongated along the field lines ($k_\parallel / k_\perp \ll 1$)
- Local radial coordinate x, local field line label y, coordinate along the field line ζ

Excitation of microinstabilities

- Strength depends on the temperature ratio (T_e/T_i) and the normalized gradients

$$\frac{a}{L_{n_s}} = -\frac{a}{n_s}\frac{\partial n_s}{\partial r}\bigg|_{r_0}$$

$$\frac{a}{L_{T_s}} = -\frac{a}{T_s}\frac{\partial T_s}{\partial r}\bigg|_{r_0}$$



Most important microinstabilities

- Ion temperature gradient driven modes (ITG)
- Electron temperature gradient driven modes (ETG)
- Trapped electron modes driven by the density or electron temperature gradient (TEM)

Modeling turbulent transport with `stella`

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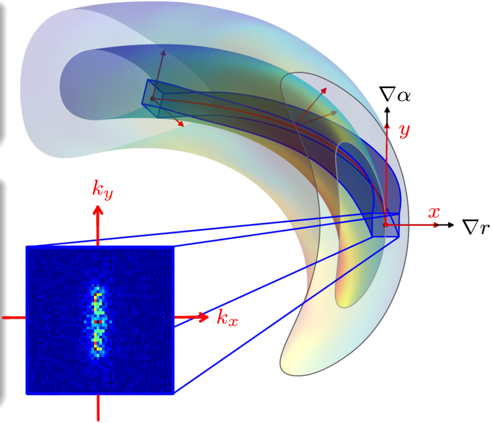

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Overview

Motivation: Turbulent transport avoids core particle depletion

Thermonuclear fusion

- Understand, predict and control transport
- Particle transport: $\Gamma_s = \Gamma_s^{\text{neo}} + \Gamma_s^{\text{turb}} + \cancel{\Gamma_s^{\text{clas}}}$

Neoclassical transport in W7-X

- Designed for reduced neoclassical transport
- Neoclassical transport is still important at the core due to the high temperatures
- Core depletion, hollow density profiles in the absence of particle sources [Maaßberg, 1999]

Discharges in W7-X

- Measured density profiles are not as hollow as neoclassical transport and particle source estimates predict
- Therefore, a significant inward contribution to the particle flux may be missing in the core

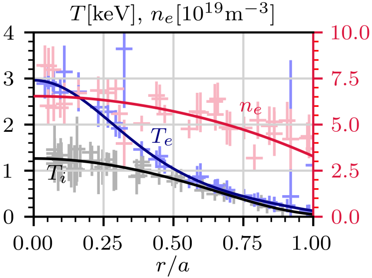
Objective

- Does turbulence drive inward particle fluxes?

Outline of the talk

- Neoclassical particle transport and the prediction of hollow density profiles
- Turbulent particle transport and the prediction of an inward particle flux: robust general mechanism
- Compare experimental, neoclassical and turbulent fluxes for #20180920.017

Discharge #20180920.017 with ECRH



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Neoclassical transport predicts very hollow density profiles in all large reactors

Neoclassical transport theory at the core

- At low collisionality we have e.g. [Beidler, 2011]

$$\frac{\Gamma_s^{\text{neo}}}{n_s} = L_{11}^s \left(\frac{1}{n_s}\frac{\mathrm{d}n_s}{\mathrm{d}r} - \frac{Z_s e E_r}{T_s} + \delta_{12}^s \frac{1}{T_s}\frac{\mathrm{d}T_s}{\mathrm{d}r} \right)$$

- Assume steady-state, no sources, ambi-polarity

$$\Gamma_i^{\text{neo}} = \Gamma_e^{\text{neo}} = 0$$

- Electrons in the $1/\nu$ and ions in the $\sqrt{\nu}$ asymptotic neoclassical regime [Beidler, 2018]

$$\frac{1}{n_i}\frac{\mathrm{d}n_i}{\mathrm{d}r} = \frac{1}{n_e}\frac{\mathrm{d}n_e}{\mathrm{d}r} = -\frac{7/2}{T_e+T_i}\frac{\mathrm{d}T_e}{\mathrm{d}r} - \frac{5/4}{T_e+T_i}\frac{\mathrm{d}T_i}{\mathrm{d}r}$$

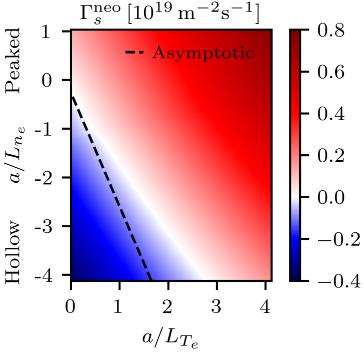
Fusion relevant neoclassically-dominated plasmas

- Peaked temperature profile: $\mathrm{d}T_s/\mathrm{d}r < 0$
- Predicts very hollow density profiles: $\mathrm{d}n_s/\mathrm{d}r > 0$
- Even with estimates for non-zero particle source

Experimental ECRH plasmas in W7-X

- Flat or weakly peaked density profiles are generally measured [Wolf, 2017]

Neoclassical particle flux with `KNOSOS`



Standard W7-X configuration at $r/a = 0.25$, $n_e = n_i = 6.4 \times 10^{19}$ m^{-3}, $T_e = 2.4$ keV, $T_i = 1.2$ keV, $a/L_{T_i} = 0.63$

Neoclassical theory is not sufficient

- Missing a significant inward contribution to Γ_s

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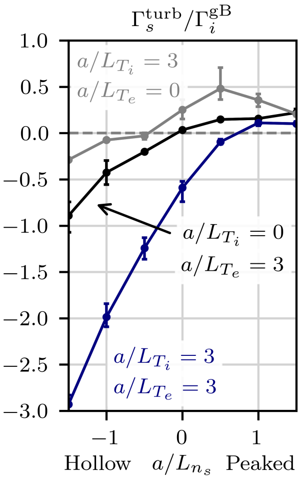
Inward convection and peaked equilibrium density driven by turbulence

Turbulent particle flux



Standard W7-X at $r/a = 0.25$, `stella`, flux-tube, kinetic ions and electrons. *

General expression for the particle flux

- Diffusion $(D > 0)$
- Convection (V) *

$$\frac{\Gamma_s^{\text{turb}}}{n_s} = -D\,\frac{1}{n_s}\,\frac{dn_s}{dr} + V$$

Diffusion (D) driven by turbulence

- Sufficiently peaked density profiles: $\Gamma_s^{\text{turb}} > 0$
- Sufficiently hollow density profiles: $\Gamma_s^{\text{turb}} < 0$

Convection (V) for flat density profile

- Turbulence driven by one temperature gradient: $V > 0$
- Turbulence driven by both temperature gradients: $V < 0$

In equilibrium if $\Gamma_s^{\text{turb}} + \Gamma_s^{\text{neo}} = 0$ (assuming $S = 0$)

- Neoclassical theory predicts very hollow density profiles due to the large outward neoclassical convection
- Turbulent inward diffusion reduces hollowness, but can not cause flat or peaked density profiles
- Turbulent inward convection that equals (overcomes) neoclassical convection can cause flat (peaked) n_s

Inward convection and peaked equilibrium density driven by turbulence

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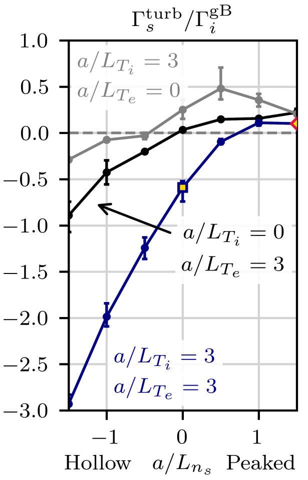

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Robustness of the sign of the convection: Dependence on a/L_{T_i}, a/L_{T_e}, T_e/T_i

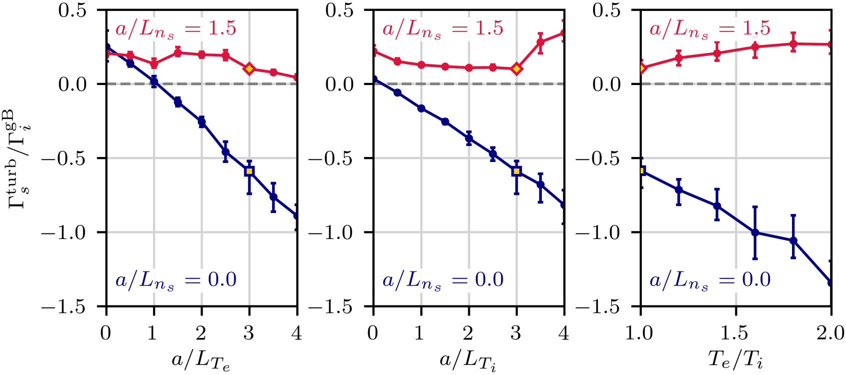
Flat density profile (blue)

- Inward fluxes when $a/L_{T_i} = 3$ and $a/L_{T_e} > 1.0$
- Inward fluxes when $a/L_{T_e} = 3$ and $a/L_{T_i} > 0.2$
- Increasing a/L_{T_i}, a/L_{T_e} or T_e/T_i increases $|\Gamma_s^{\text{turb}}|$

Peaked density profile (red)

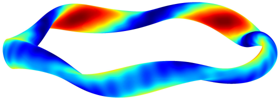
- Outward particle flux due to $-D\, n_s'$
- Small effect of a/L_{T_i}, a/L_{T_e} or T_e/T_i on the particle flux$\,*$

Turbulent particle flux with `stella` with $a/L_{T_i} = 3$; $a/L_{T_e} = 3$ and $T_e/T_i = 1$



Robustness of the sign of the convection: Dependence on magnetic geometry

W7-X



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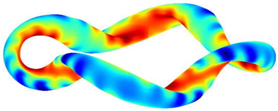

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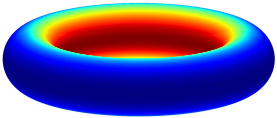

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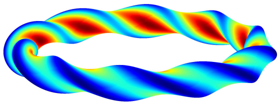

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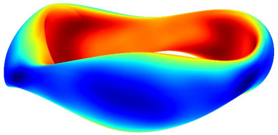

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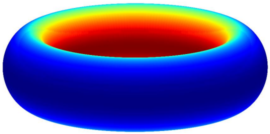

Robustness of the sign of the convection: Dependence on magnetic geometry

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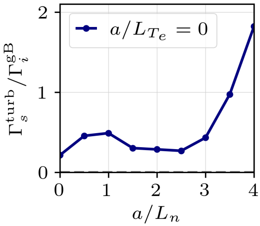

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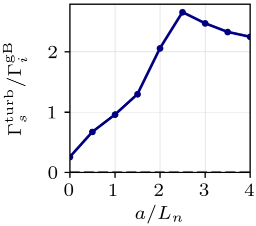

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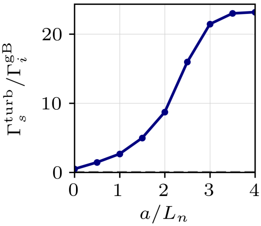

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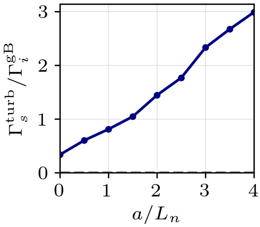

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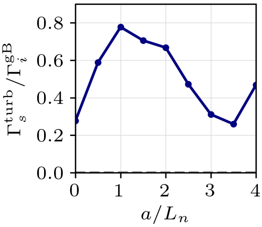

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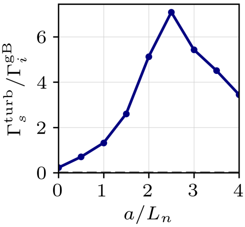
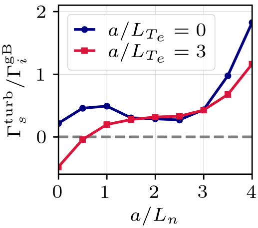


The sign of the convection is independent of the magnetic geometry $(r/a=0.7)$

W7-X



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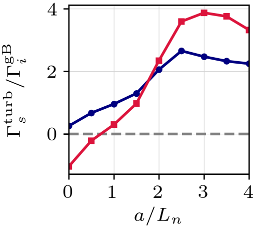

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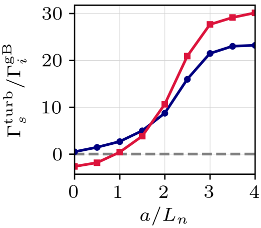

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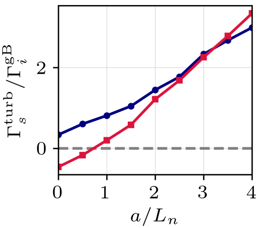

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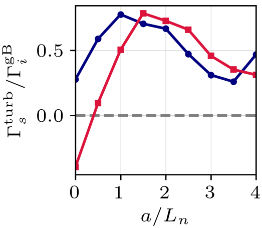

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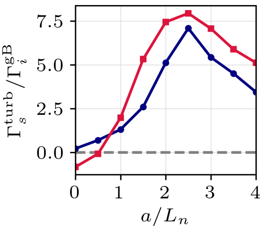


Correlation of sgn(Γ_s^{turb}) with the phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$

Particle flux spectrum and phase-shift arg($\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}$) for $a/L_n = 0$

- $a/L_{T_e} = 0$: dominant outward peak to the particle flux, the tail (small scales) is negative
- $a/L_{T_e} = 3$: small outward peak at large scales, followed by a big inward peak

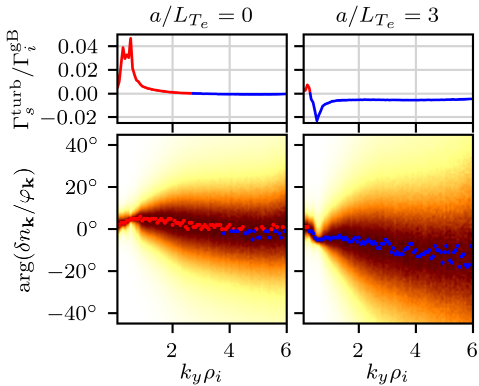
Phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$

- arg($\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}$) $> 0 \Leftrightarrow \Gamma_s^{\text{turb}} > 0$
- arg($\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}$) $< 0 \Leftrightarrow \Gamma_s^{\text{turb}} < 0$
- Inward fluxes: $\delta n_{\mathbf{k}}$ lags behind $\varphi_{\mathbf{k}}$

Particle flux spectrum for $a/L_n \neq 0$

- For sufficiently peaked profiles, all scales drive outward particle fluxes due to diffusion
- For sufficiently hollow profiles, all scales drive inward particle fluxes due to diffusion

Flat density profile $(a/L_n = 0)$



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- $a/L_{T_e} = 3$: small outward peak at large scales, followed by a big inward peak

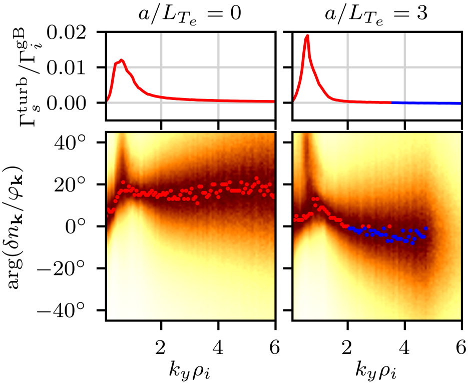
Phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$

- arg$(\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}) > 0 \;\Leftrightarrow\; \Gamma_s^{\text{turb}} > 0$
- arg$(\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}) < 0 \;\Leftrightarrow\; \Gamma_s^{\text{turb}} < 0$
- Inward fluxes: $\delta n_{\mathbf{k}}$ lags behind $\varphi_{\mathbf{k}}$

Particle flux spectrum for $a/L_n \neq 0$

- For sufficiently peaked profiles, all scales drive outward particle fluxes due to diffusion
- For sufficiently hollow profiles, all scales drive inward particle fluxes due to diffusion

Peaked density profile $(a/L_n = 1.5)$



Correlation of sgn(Γ_s^{turb}) with the phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$

Particle flux spectrum and phase-shift arg($\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}$) for $a/L_n = 0$

- $a/L_{T_e} = 0$: dominant outward peak to the particle flux, the tail (small scales) is negative
- $a/L_{T_e} = 3$: small outward peak at large scales, followed by a big inward peak

Phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$ *

- arg($\delta n_{\mathbf{k}}/\varphi_{\mathbf{k}}$) $> 0 \;\Leftrightarrow\; \Gamma_s^{\text{turb}} > 0$
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Particle flux spectrum for $a/L_n \neq 0$

- For sufficiently peaked profiles, all scales drive outward particle fluxes due to diffusion
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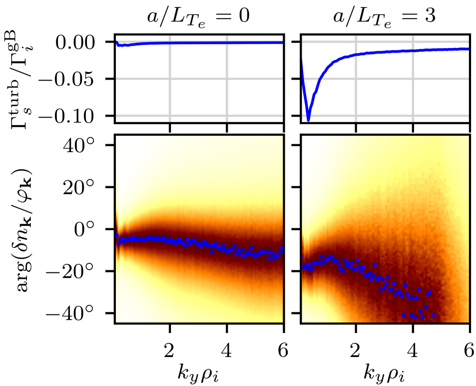
Hollow density profile ($a/L_n = -1.5$)



Overview

1. Introduction
   - The stellarator: candidate concept for fusion reactors
   - Importance of neoclassical and turbulent transport
   - Modeling turbulent transport with `stella`
2. Motivation for the study of the effect of turbulence on stellarator particle transport
3. Neoclassical particle transport
4. Turbulent particle transport
   - Turbulence can drive inwards convection
   - Dependence on $a/L_n, a/L_{T_i}, a/L_{T_e}$ and T_e/T_i
   - Dependence on the magnetic geometry
   - Correlation of $\mathrm{sgn}(\Gamma_s^{\mathrm{turb}})$ with the phase-shift between $\delta n_{\mathbf{k}}$ and $\varphi_{\mathbf{k}}$
5. Analysis of ECRH discharge in W7-X
6. Conclusions and prospects

Analysis of ECRH discharge (#20180920.017) from OP1 in W7X

Experimental particle flux

- Neutral ionization source: recycling neutrals [Kremeyer'22]
- Short-mean-free-path 1D neutral transport model

$$\frac{d}{dr} r D_{CX} \left(\frac{dn_0}{dr} + \frac{1}{T_0} \frac{dT_0}{dr} n_0 \right) = 2 r \nu_{ion} n_0$$

- τ_p is varied from 0.1 s to 1.0 s to account for uncertainties in the confinement time [Beurskens 2021]
- Γ_s^{exp} is determined from neutral particle source $n_0(r)$
- Γ_s^{neo} (`DKES`) does not match Γ_s^{exp} at the core (nor edge)

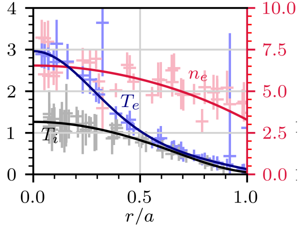
Compare $\Gamma_s^{\text{exp}} - \Gamma_s^{\text{neo}}$ with Γ_s^{turb} (`stella`)

- sign(Γ_s^{turb}) agrees with sign($\Gamma_s^{\text{exp}} - \Gamma_s^{\text{neo}}$) for $\tau_p \approx 1$ s
- Possible sources of quantitative disagreements: plasma profiles, model (flux-tube, ion-scales, collisionless), ... *

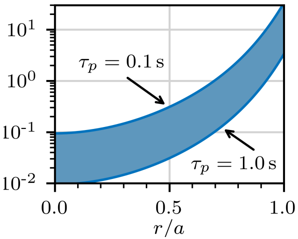
Turbulence driven by both temperature gradients

- Can explain the missing inward flux in the core and the missing outward flux at the edge *

Profiles T[keV], $n_e[10^{19}\text{m}^{-3}]$



Neutral density n_0 $[10^{14}\text{m}^{-3}]$



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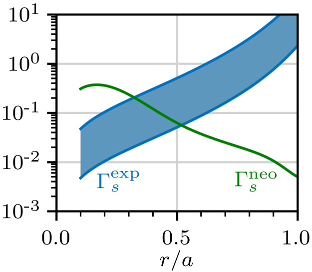
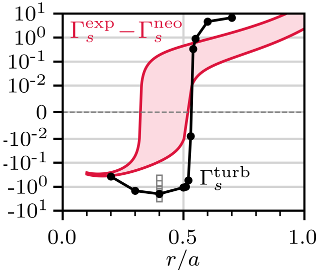
Turbulence driven by both temperature gradients

- Can explain the missing inward flux in the core and the missing outward flux at the edge *

Γ_s $[10^{19}\text{m}^{-2}\text{s}^{-1}]$





Conclusions and prospects

Neocl. theory is probably not sufficient to explain particle transport in the core of stellarators

- The neoclassical particle flux leads to strongly hollow density profiles
- Flat and weakly peaked density profiles are generally measured in W7-X
- Therefore, an inward contribution to the particle flux is missing in the core

Turbulence can drive inward fluxes at the core (in W7-X, NCSX, TJ-II, LHD, AUG and CBC)

- With `stella` we have identified the turbulence driven by both temperature gradients as the mechanism that leads to inward convection and could sustain peaked density profiles
- The magnitude of the inward convection increases with increasing a/L_{T_i}, a/L_{T_e} and T_e/T_i
- Neglecting dT_e/dr in the problem systematically yields outward turbulent particle fluxes *

Analysis of ECRH discharge (#20180920.017) from OP1 in W7-X

- With the available estimates of τ_p, Γ_s^{neo} alone is not able to explain the particle fluxes
- `stella` simulations can explain qualitatively the experimental particle flux both at the edge, where turbulence provides an extra outward flux, and the core where it drives an inward flux

Future and prospects

- Experiments are planned for W7-X and TJ-II to validate the predicted parametric dependence
- Determine (D_{Z1}, D_{Z2}, C_Z) from $\Gamma_Z = -n_Z[D_{Z1}(d\ln n_z/dr) + D_{Z2}(d\ln T_z/dr) + C_z]$?

Thank you for your attention!

[H. Thienpondt, JM. García-Regaña, I. Calvo, JA. Alonso, JL. Velasco, A. González-Jerez, M. Barnes, K. Brunner, O. Ford, G. Fuchert, et al. Prevention of core particle depletion in stellarators by turbulence. *Physical Review Research*, 5(2):L022053, 2023]

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