Insights from massive gyrokinetic simulations and experimental measurements of turbulent transport in Wendelstein 7-X

H. Thienpondt[1], J. M. García-Regaña[1], I. Calvo[1],
M. Wappl[2], S. Bozhenkov[2]

[1]Laboratorio Nacional de Fusión, CIEMAT, Spain
[2]Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

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Overview

1. Motivation
2. **Obtain insights from large-scale gyrokinetic simulations using academical scans for different W7-X configurations**
   - Stella simulations for fixed plasma parameters in W7-X, NCSX, LHD, TJ-II and HSX
   - Stella simulations for fixed plasma parameters in different configurations of W7-X
   - Agreement between academical scans and experimental observations
3. **Obtain insights from large-scale gyrokinetic simulations based on the experimental database for W7-X**
   - Construct database of simulated turbulent heat and particle transport for W7-X
   - Dependence of turbulent heat transport on density gradients
   - Dependence of turbulent heat transport on temperature gradients
   - Inward turbulent particle flux
4. Conclusions

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Motivation: validation of experimental observations of turbulent transport in W7-X

Wendelstein 7-X stellarator

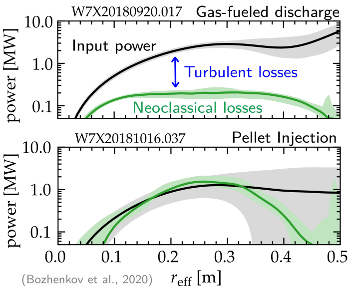
- Optimized to have **reduced neoclassical transport** (Beidler et al., 2021)
- Relative importance of **turbulent transport** has increased, which can now dominate over the entire plasma radius (Bozhenkov et al., 2020)

Experimental observations for turbulent heat transport in W7-X

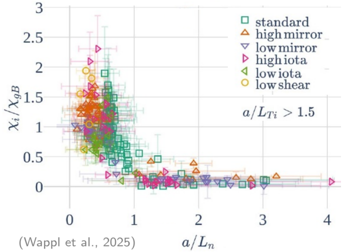
- Experiments suggest that **turbulent heat losses are reduced by peaked density profiles** (large density gradients) (Bozhenkov et al., 2020)
- Recently, a **large-scale experimental database** has demonstrated that **turbulent heat losses are reduced by density peaking** (Wappl et al., 2025)

Validation of experimental observations with gyrokinetic simulations

- Validation of experiments are typically limited to 1 (or 2) experimental discharges, while academical scans tend to only cover a small part of the experimental parameter space (geometry and plasma parameters)
- Objective: obtain insights from **large-scale gyrokinetic simulations** based on **academical scans** considering different W7-X configurations, and the **experimental database** for W7-X published in (Wappl et al., 2025)



(Bozhenkov et al., 2020)



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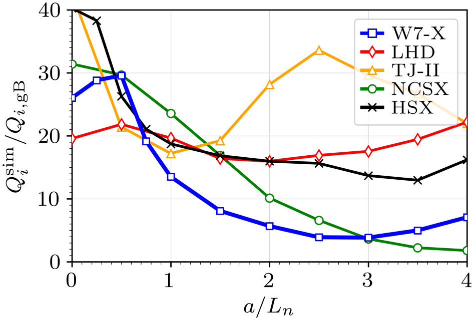
Investigated the effect of density peaking in LHD, TJ-II, NCSX and W7-X in [Thienpondt, NF'2025] and HSX

- Gyrokinetic simulations: electrostatic, flux tube, ion scales, no collisions, $a/L_{T_i} = 3.0$, $a/L_{T_e} = 3.0$, $r/a = 0.7$
- In this work, these results are expanded to different W7-X configurations and compared with experimental data

Ion heat flux [Thienpondt, NF'2025]



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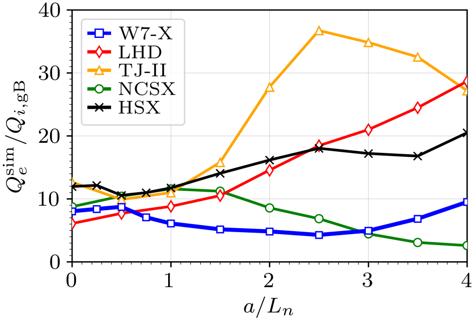

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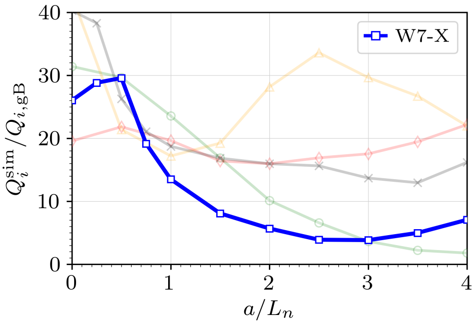

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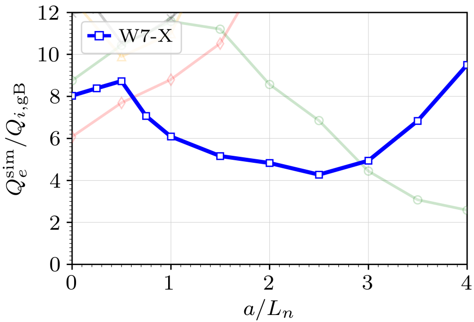

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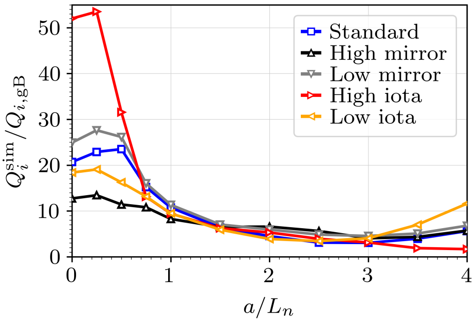
Stella simulations for fixed plasma parameters in different configurations of W7-X

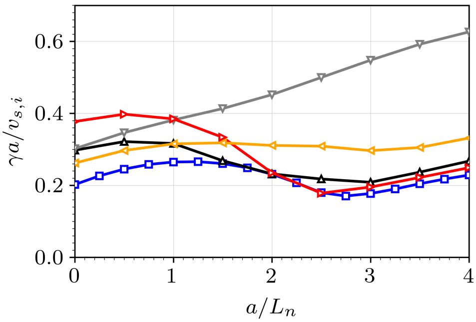
Investigate the effect of density peaking in different W7-X configurations

- Gyrokinetic simulations: electrostatic, flux tube, ion scales, no collisions, $a/L_{T_i} = 3.0$, $a/L_{T_e} = 3.0$, $r/a = 0.7$
- No correlation between linear growth rates and nonlinear ion heat fluxes

Ion heat flux



Growth rate ($k_x\rho_i = 0$ and $k_y\rho_i \leq 1.4$)

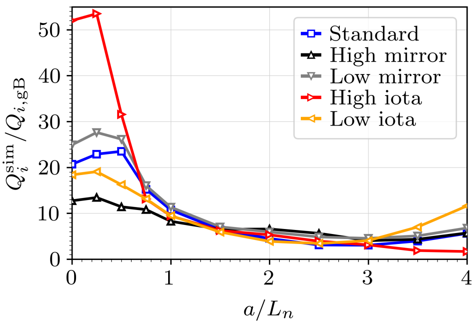


Stella simulations for fixed plasma parameters in different configurations of W7-X

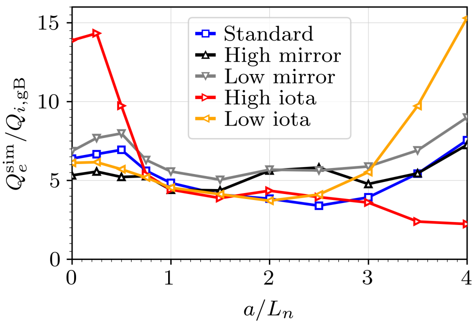
Investigate the effect of density peaking in different W7-X configurations

- Reduction of ion (and electron) heat flux with density peaking is found in every examined W7-X configuration
- Significant ion heat fluxes for $a/L_n \leq 1.0$, and reduced ion heat fluxes for $a/L_n \geq 1.0$ up to $a/L_n \approx 3.0$

Ion heat flux



Electron heat flux

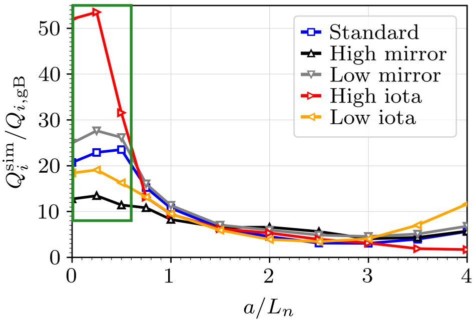


Stella simulations for fixed plasma parameters in different configurations of W7-X

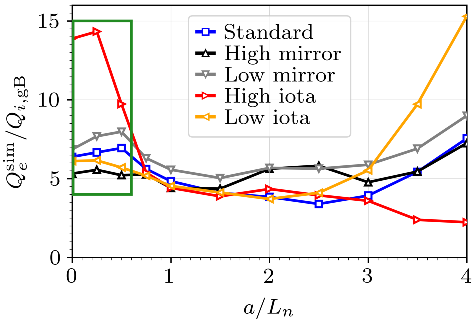
Turbulent heat transport in the presence of small density gradients (mostly driven by $a/L_{T_i} = a/L_{T_e} = 3.0$)

- Relatively large in **Low Mirror** and **High Iota** configurations
- Relatively small in **High Mirror** and **Low Iota** configurations

Ion heat flux



Electron heat flux

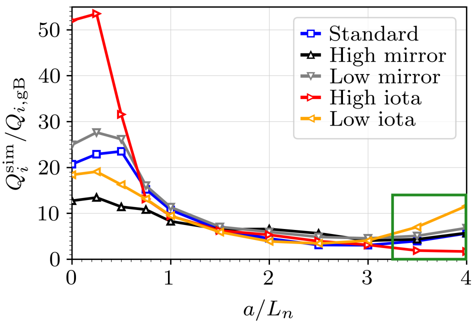


Stella simulations for fixed plasma parameters in different configurations of W7-X

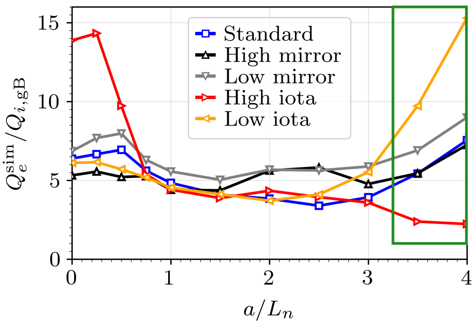
Turbulent heat transport in the presence of large density gradients (mostly driven by $a/L_n = 4.0$)

- Relatively large in the **Low Iota** configuration
- Relatively small in the **High Iota** configuration

Ion heat flux



Electron heat flux

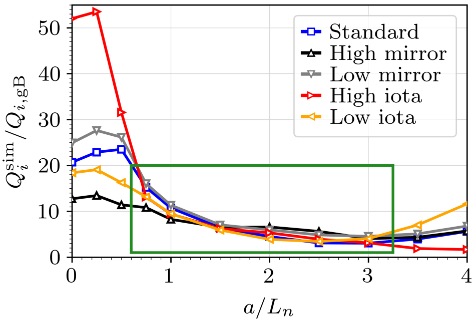


Stella simulations for fixed plasma parameters in different configurations of W7-X

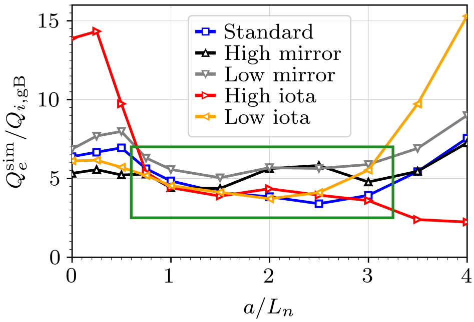
Turbulent heat transport in the presence of moderate density gradients considering $a/L_{T_i} = a/L_{T_e} = 3.0$

- Within $0.75 \leq a/L_n \leq 3.0$ the configuration effect on the turbulent heat transport is minimal
- Clear differences between configurations emerge for $a/L_n \leq 0.5$ and $a/L_n \geq 3.5$

Ion heat flux ($a/L_{T_i} = a/L_{T_e} = 3.0$)



Electron heat flux ($a/L_{T_i} = a/L_{T_e} = 3.0$)

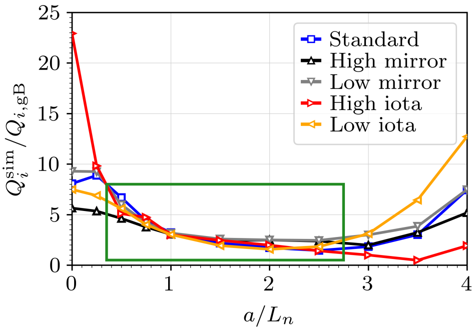


Stella simulations for fixed plasma parameters in different configurations of W7-X

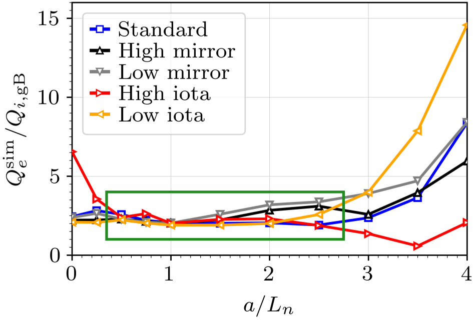
Turbulent heat transport in the presence of moderate density gradients considering $a/L_{T_i} = a/L_{T_e} = 2.0$

- Within $0.5 \leq a/L_n \leq 2.5$ the configuration effect on the turbulent heat transport is minimal
- Clear differences between configurations emerge for $a/L_n \leq 0.25$ and $a/L_n \geq 3.0$

Ion heat flux ($a/L_{T_i} = a/L_{T_e} = 2.0$)



Electron heat flux ($a/L_{T_i} = a/L_{T_e} = 2.0$)

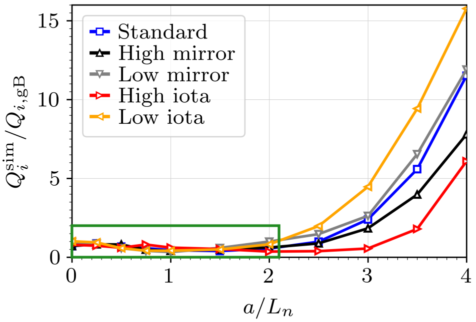


Stella simulations for fixed plasma parameters in different configurations of W7-X

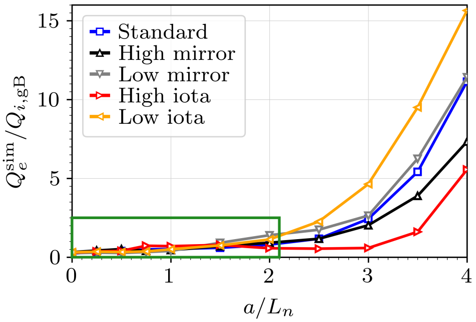
Turbulent heat transport in the presence of moderate density gradients considering $a/L_{T_i} = a/L_{T_e} = 1.0$

- Within $0.0 \leq a/L_n \leq 2.0$ the configuration effect on the turbulent heat transport is minimal
- Clear differences between configurations emerge for $a/L_n \geq 2.5$

Ion heat flux ($a/L_{T_i} = a/L_{T_e} = 1.0$)



Electron heat flux ($a/L_{T_i} = a/L_{T_e} = 1.0$)

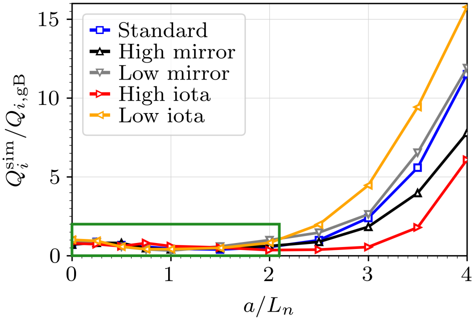


Stella simulations for fixed plasma parameters in different configurations of W7-X

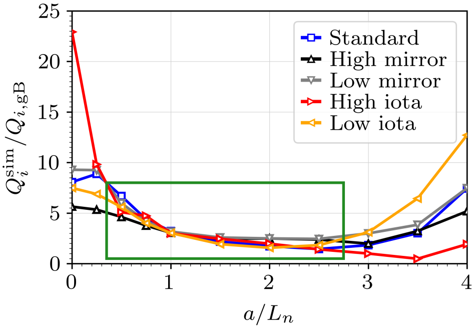
Investigate the effect of density peaking in different W7-X configurations

Differences between W7-X configurations in turbulent heat transport are expected to appear in the presence of sufficiently large ion temperature or density gradients. Nonetheless, across a broad range of $(a/L_{T_i}, a/L_n)$ gradients, the configuration effect on heat transport is expected to be minimal.

Ion heat flux ($a/L_{T_i} = a/L_{T_e} = 1.0$)



Ion heat flux ($a/L_{T_i} = a/L_{T_e} = 2.0$)



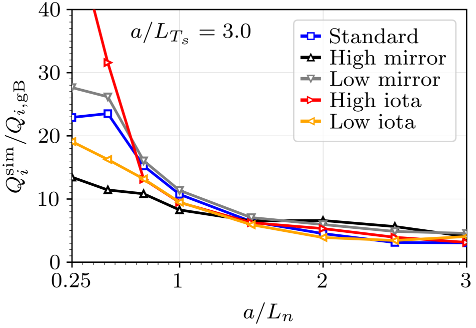
Overview

Objective: obtain insights from large-scale gyrokinetic simulations based on experimental database

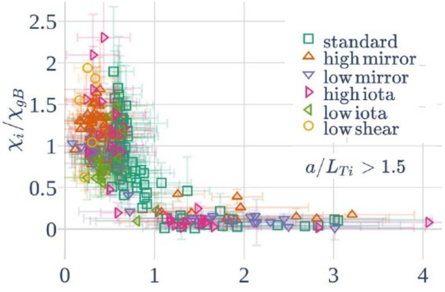
Similar trend is observed in the academical scans and experimental database

- Reduction of ion heat flux with density peaking is found, independent of the magnetic configuration
- Significant ion heat fluxes for $a/L_n \leq 1.0$, and reduced ion heat fluxes for $a/L_n \geq 1.0$

Simulated ion heat flux



Experimental ion heat diffusivity [Wappl, 2025]



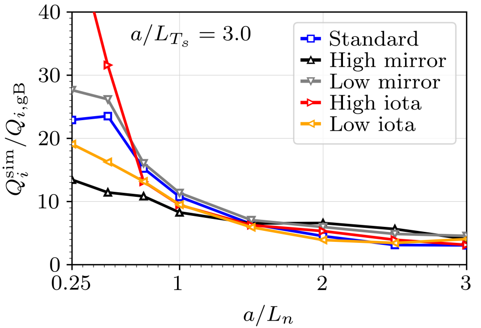
(Wappl et al., 2025)

Objective: obtain insights from large-scale gyrokinetic simulations based on experimental database

In this work, we build a simulated database based on the experimental plasma parameters

- Validate the gyrokinetic code `stella` against experimental measurements from W7-X
- Investigate correlations between the turbulent heat/particle transport and experimental plasma parameters

Simulated ion heat flux



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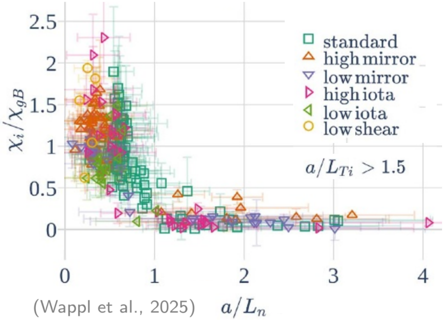

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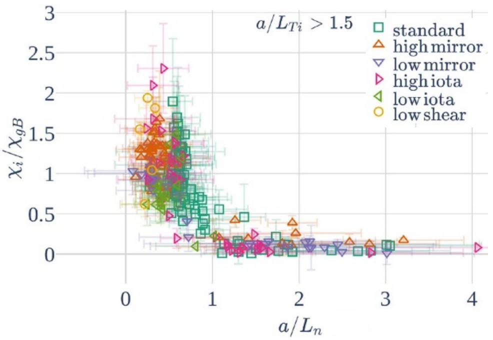
Database of experimental turbulent heat transport for W7-X

Database of experimental turbulent heat transport for W7-X has been published in [Wappl, PPCF'2025]

- Considered 318 data points, taken from 153 W7-X discharges of OP1.2b, OP2.1 and OP2.3 at $r/a = 0.5$
- Turbulent heat diffusivity is computed from power balance (heating sources, neoclassical losses, radiated power)

Experimental ion heat diffusivity [Wappl, 2025]



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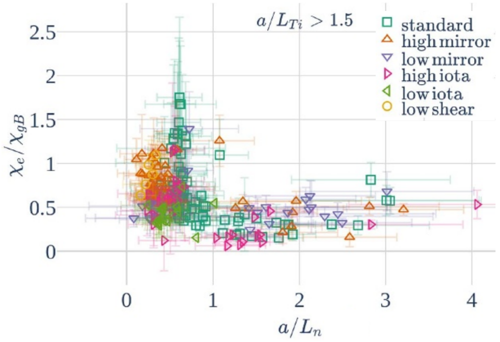

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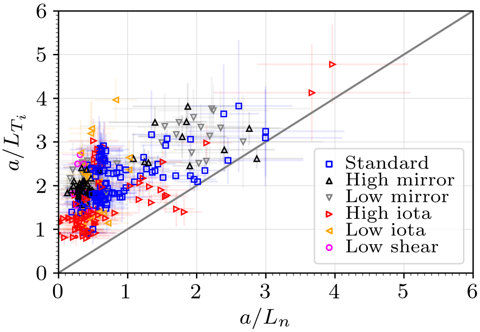
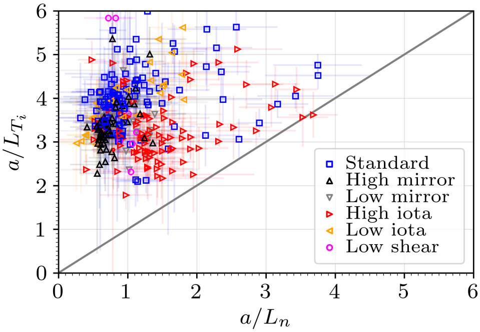
- This work considers 2*318 data points, taken from 153 W7-X discharges, evaluated at $r/a = 0.5$ and $r/a = 0.7$
- Turbulent heat diffusivity is computed from power balance (heating sources, neoclassical losses, radiated power)

Experimental data points at $r/a = 0.5$ [Wappl, 2025]



Experimental data points at $r/a = 0.7$ [Wappl, 2025]



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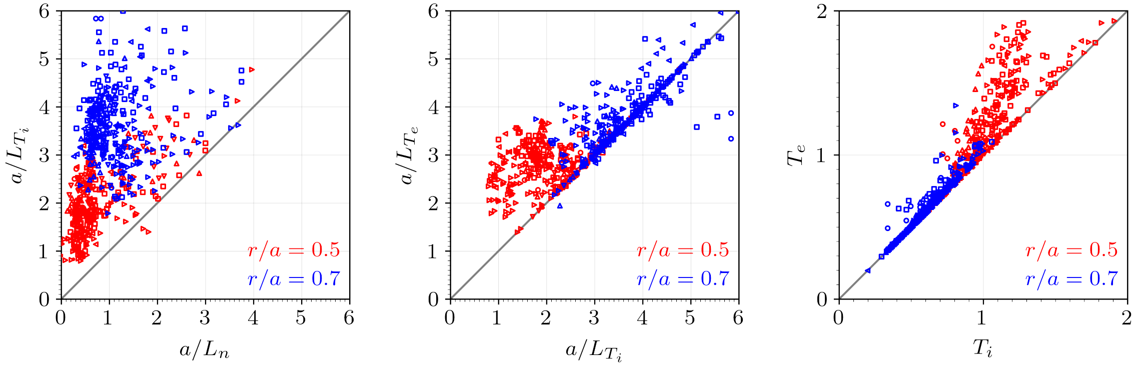
- This work considers 2*318 data points, taken from 153 W7-X discharges, evaluated at $r/a = 0.5$ and $r/a = 0.7$
- Turbulence is most likely ITG-driven ($a/L_{T_i} > a/L_n$) and temperature profiles are not necessarily equalized

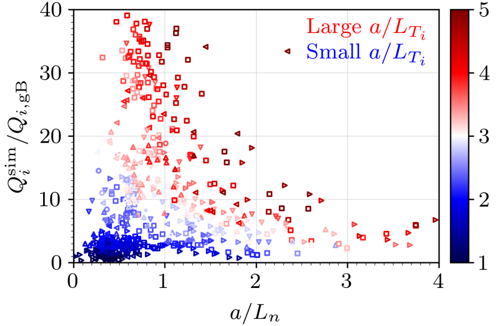


Database of simulated turbulent heat transport for W7-X

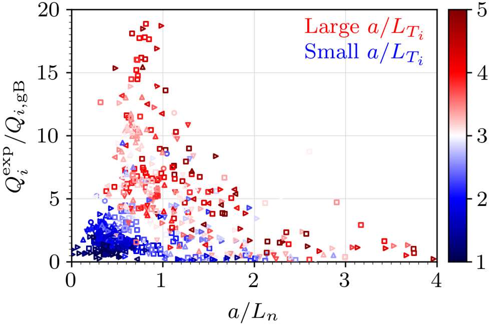
Calculate the turbulent heat transport with `stella` (nonlinear, electrostatic, flux tube, no collisions)

- Use the experimental plasma parameters (n_i, n_e, T_e, T_i, a/L_n, a/L_{T_i}, a/L_{T_e})
- Consider the W7-X configuration at the radial locations $r/a = 0.5$ and $r/a = 0.7$ (using 47 unique `VMEC` files)

Simulated ion heat flux



Experimental ion heat flux



Quantitative agreement between simulated and experimental database

Comparison of simulated and experimental database

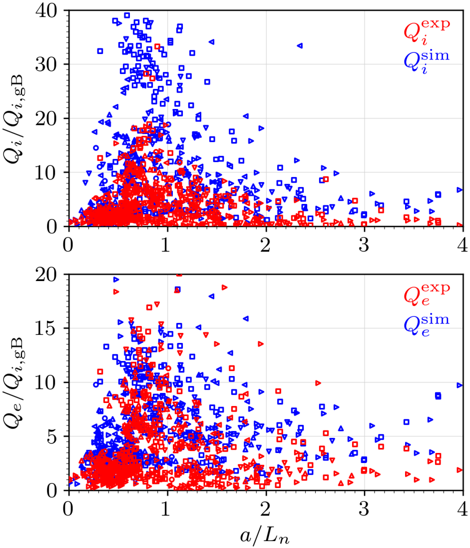
- Flux-tube gyrokinetic simulations tend to overestimate the ion heat flux, which is widely observed in the community
- Order of magnitude of electron heat flux is predicted well

Gyrokinetic simulations with `stella`

- Consider nonlinear, flux-tube, electrostatic simulations, which only consider ion-scales and do not include collisions
- Simulations do not take into account electromagnetic, multi-scale, collisional, full-flux-surface nor global effects

Experimental database

- Uncertainties on the plasma profiles can affect both the experimental and gyrokinetic predictions significantly
- The magnetic equilibria (`VMEC`) have not been generated for the exact pressure profiles, instead the closest one (in β) is chosen



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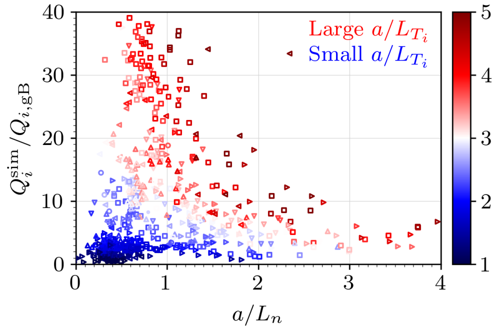
Effect of density peaking on turbulent heat transport: ion heat flux

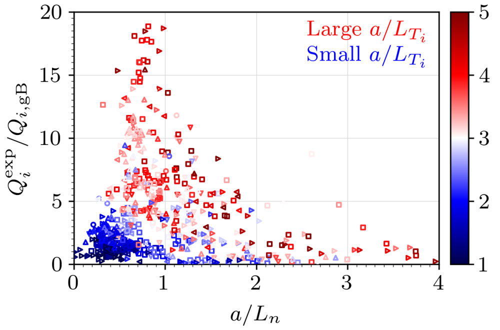
Simulated and experimental ion heat flux at $r/a = 0.5$ and $r/a = 0.7$

- Reduction of ion heat flux with density peaking is observed in both databases
- Trend depends significantly on ion temperature gradient $\Rightarrow$ valley of reduced heat losses around $a/L_{T_i} \approx a/L_n$

Simulated ion heat flux



Experimental ion heat flux



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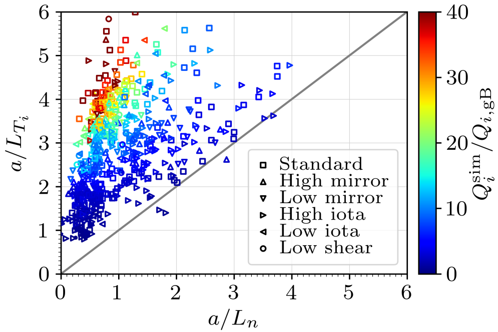
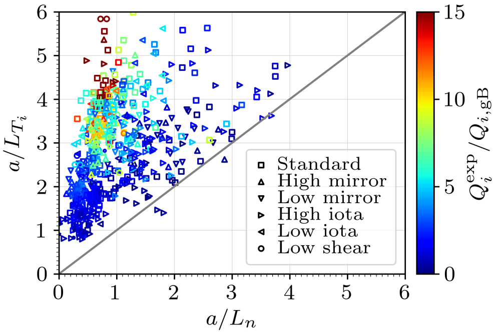
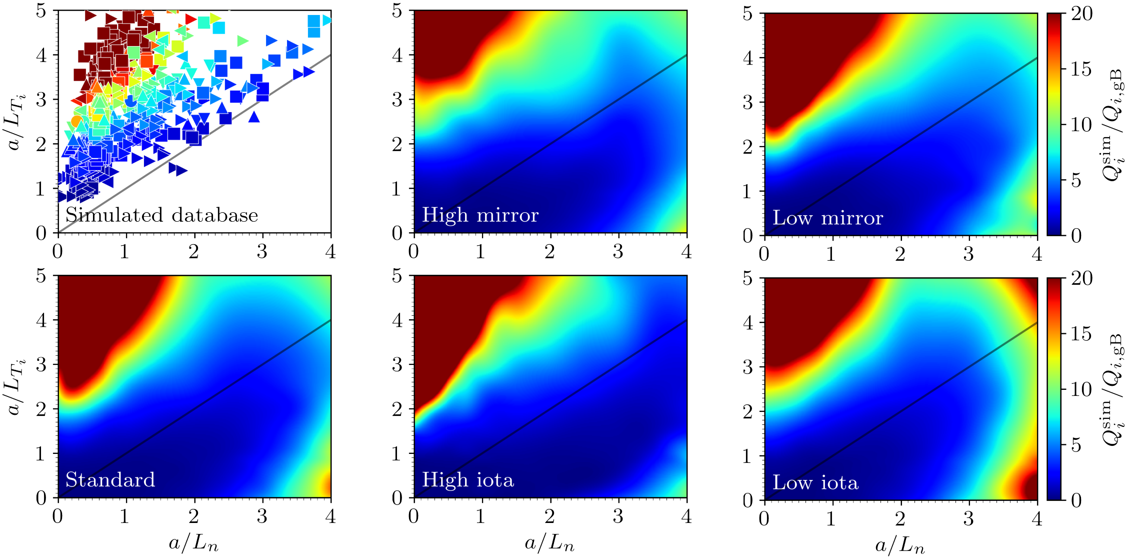


Experimental ion heat flux



Valley of reduced heat losses is present for all examined W7-X configurations

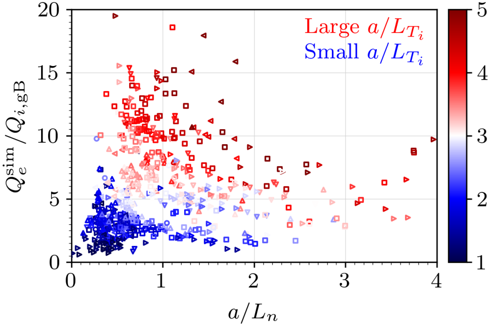


Effect of density peaking on turbulent heat transport: electron heat flux

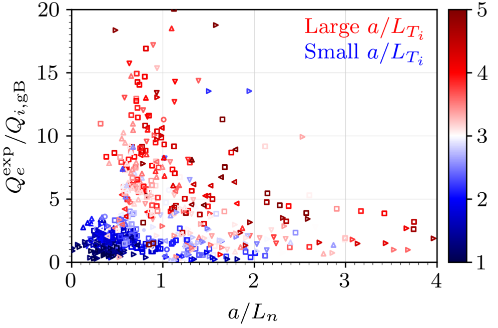
Simulated and experimental electron heat flux at $r/a = 0.5$ and $r/a = 0.7$

- Reduction of electron heat flux with density peaking is observed in both databases
- Trend depends significantly on ion temperature gradient $\Rightarrow$ valley of reduced heat losses around $a/L_{T_i} \approx a/L_n$

Simulated electron heat flux



Experimental electron heat flux



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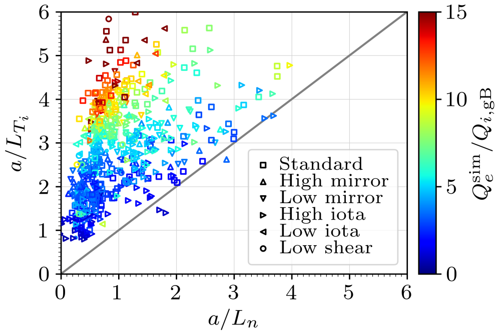
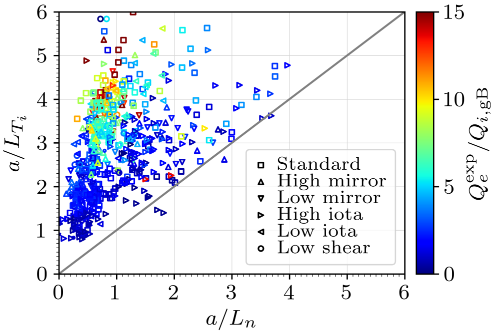


Experimental electron heat flux

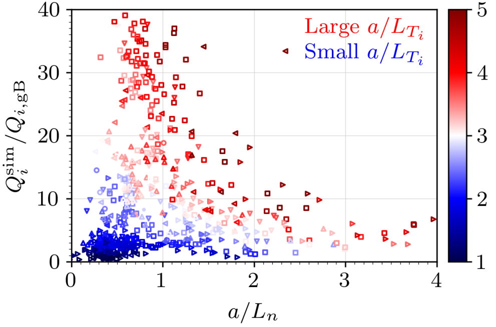


Effect of density peaking on turbulent heat transport

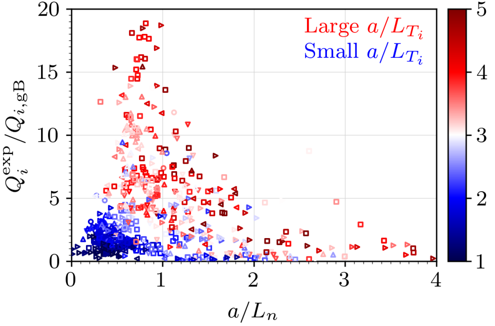
Investigate the density peaking effect using simulations and experimental measurements

The simulated and experimental ion (and electron) heat fluxes are reduced significantly by increasing density gradients. This trend depends strongly on the ion temperature gradient.

Simulated ion heat flux



Experimental ion heat flux



Overview

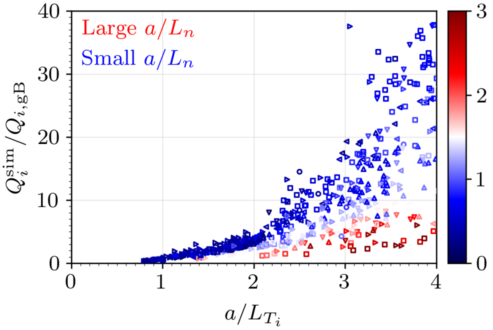
1. Motivation
2. **Obtain insights from large-scale gyrokinetic simulations using academical scans for different W7-X configurations**
   - Stella simulations for fixed plasma parameters in W7-X, NCSX, LHD, TJ-II and HSX
   - Stella simulations for fixed plasma parameters in different configurations of W7-X
   - Agreement between academical scans and experimental observations
3. **Obtain insights from large-scale gyrokinetic simulations based on the experimental database for W7-X**
   - Construct database of simulated turbulent heat and particle transport for W7-X
   - Dependence of turbulent heat transport on density gradients
   - Dependence of turbulent heat transport on temperature gradients
   - Inward turbulent particle flux
4. Conclusions

Dependence of turbulent ion heat flux on the ion temperature gradient

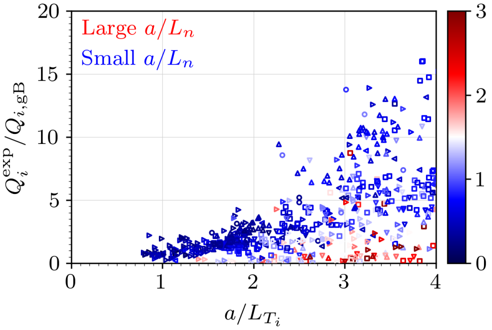
Simulated and experimental ion heat flux at $r/a = 0.5$ and $r/a = 0.7$

- Ion heat flux increases with the ion temperature gradient, while the stiffness depends on density gradient
- For ITG-driven turbulence, a critical ion temperature gradient of $a/L_{T_i} \approx 0.7$ is identified

Simulated ion heat flux



Experimental ion heat flux



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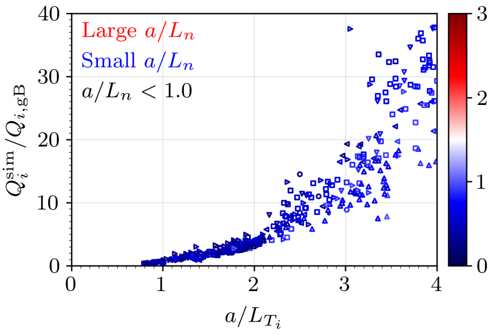
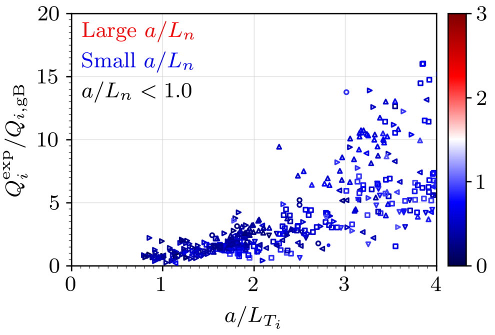


Experimental ion heat flux

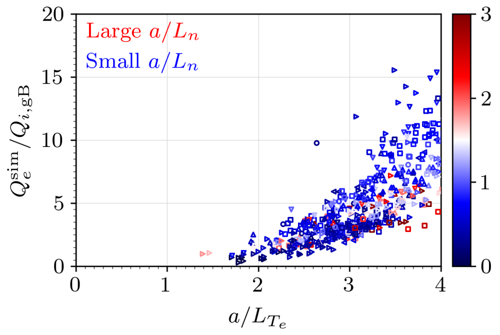


Dependence of turbulent electron heat flux on the electron temperature gradient

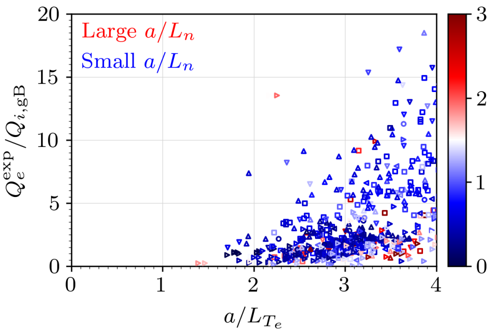
Simulated and experimental electron heat flux at $r/a = 0.5$ and $r/a = 0.7$

- **Electron heat flux increases with the electron temperature gradient**, while the stiffness depends on a/L_n
- For ITG-driven turbulence, a critical electron temperature gradient of $a/L_{T_e} \approx 1.6$ is identified

Simulated electron heat flux



Experimental electron heat flux



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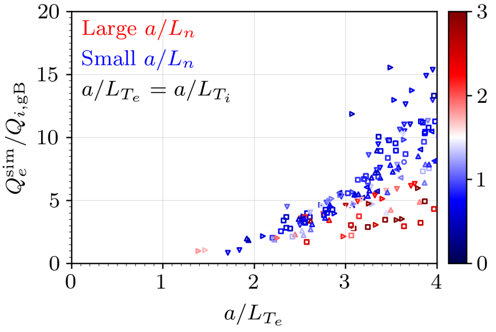
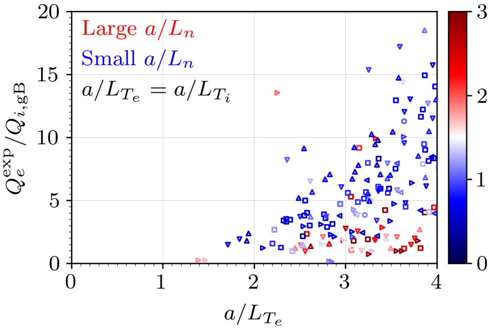
Simulated electron heat flux



Experimental electron heat flux

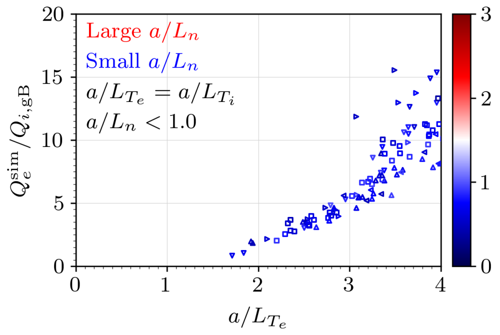


Dependence of turbulent electron heat flux on the electron temperature gradient

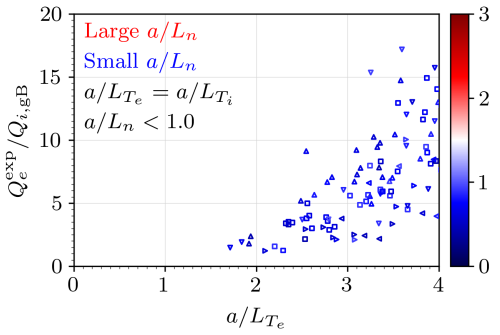
Simulated and experimental electron heat flux at $r/a = 0.5$ and $r/a = 0.7$

- Electron heat flux increases with the electron temperature gradient, while the stiffness depends on a/L_n
- For ITG-driven turbulence, a critical electron temperature gradient of $a/L_{T_e} \approx 1.6$ is identified

Simulated electron heat flux



Experimental electron heat flux



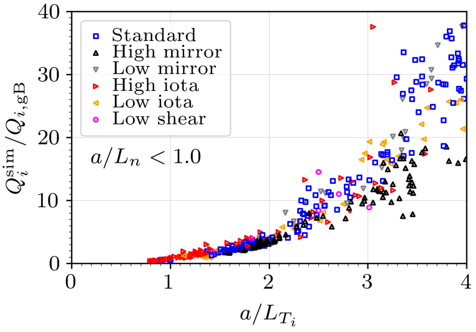
Dependence of turbulent ion heat flux on ion temperature gradient: configuration effect

Simulated heat flux at $r/a = 0.5$ and $r/a = 0.7$

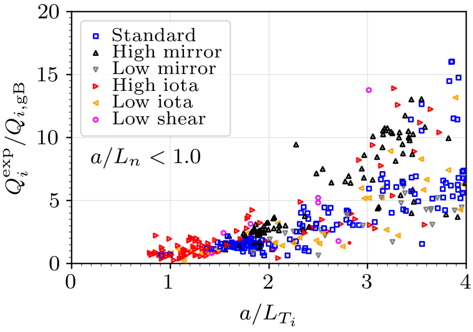
– Ion heat flux increases with the ion temperature gradient, while the stiffness depends on a/L_n

⇒ Investigate this observation using academical scans considering $a/L_n = 1$ and $a/L_{T_s} = [0, ..., 4]$

Simulated ion heat flux



Experimental ion heat flux

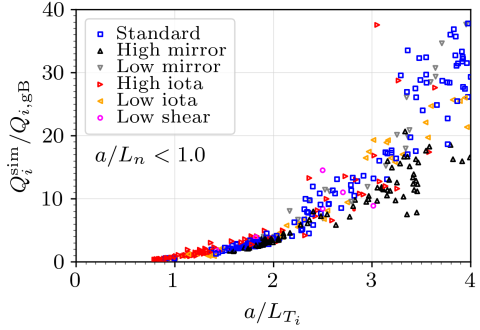


Dependence of turbulent ion heat flux on ion temperature gradient: configuration effect

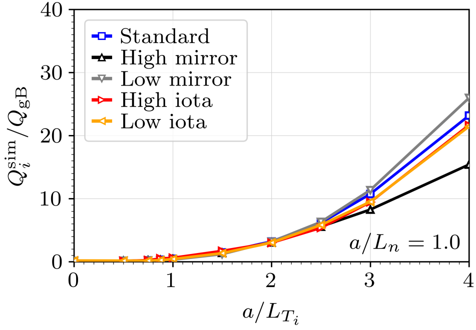
Simulated heat flux at $r/a = 0.5$ and $r/a = 0.7$

- Ion heat flux increases with the ion temperature gradient, while the stiffness depends on the density gradient
- Trend is independent of the magnetic configuration in a large range of the experimental parameter space

Simulated ion heat flux



Simulated ion heat flux ($a/L_n = 1.0$)



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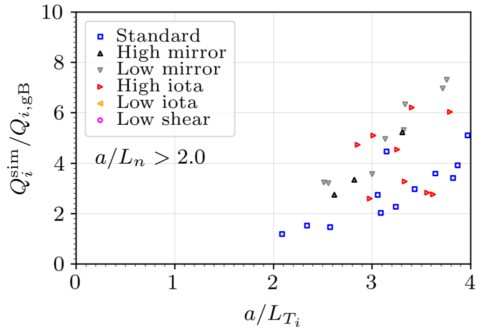
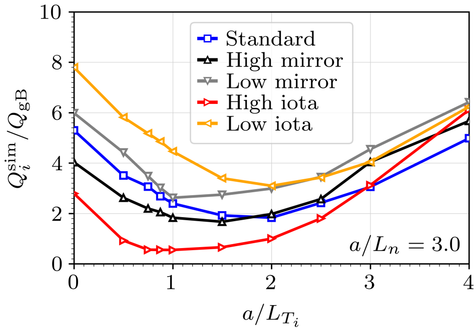


Simulated ion heat flux ($a/L_n = 3.0$)

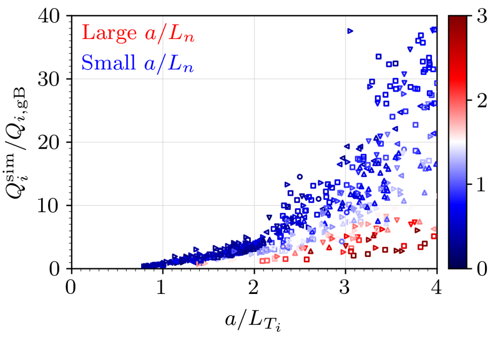


Dependence of turbulent heat transport on the temperature gradients

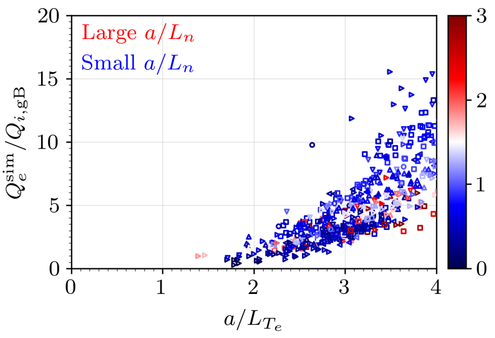
Investigate the dependence on the temperature gradients using simulations and experimental measurements

A clear dependence of the simulated (experimental) ion and electron heat fluxes on the ion and electron temperature gradients is observed, and the critical temperature gradients can easily be identified. This trend depends strongly on $\mathbf{a/L_n}$, and is mostly independent of the magnetic configuration.

Simulated ion heat flux



Simulated electron heat flux



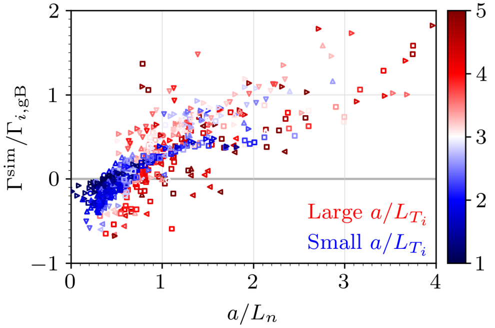
Overview

Turbulent particle flux for experimental plasma parameters

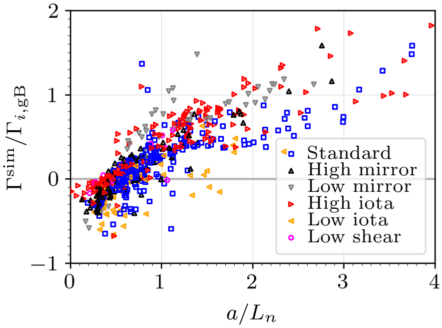
Simulated database of turbulent particle flux for W7-X

- Inward turbulent convection or particle pinch ($\Gamma < 0$ for $a/L_n = 0$) is found for all configurations
- If transport is purely due to turbulence, the density profile would be peaked ($a/L_n = 0.4$ to 0.8 for $\Gamma = 0$)

Simulated particle flux



Simulated particle flux



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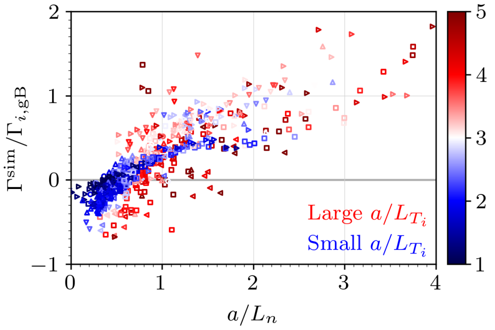

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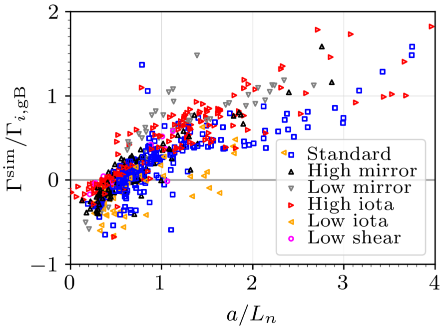
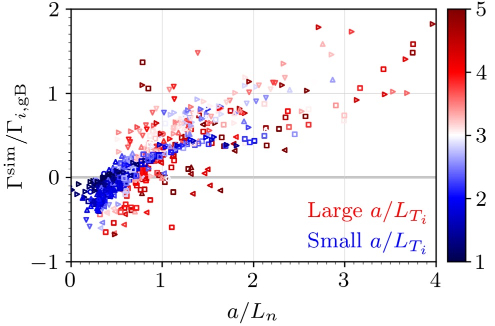


Turbulent particle flux for experimental plasma parameters: configuration effect

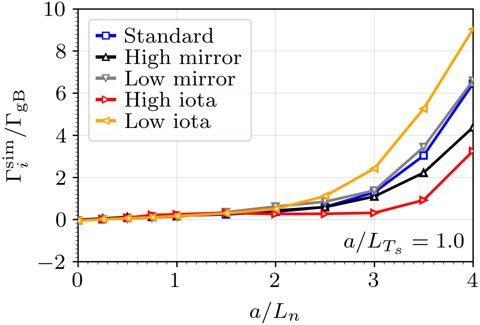
Simulated database of turbulent particle flux for W7-X

- Trend is independent of the magnetic configuration in a large range of the experimental parameter space
- Clear differences between configurations emerge for large density gradients (or large diffusion)

Simulated particle flux



Simulated particle flux ($a/L_{T_s} = 1.0$)



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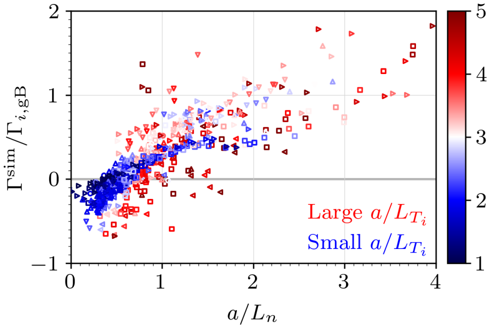
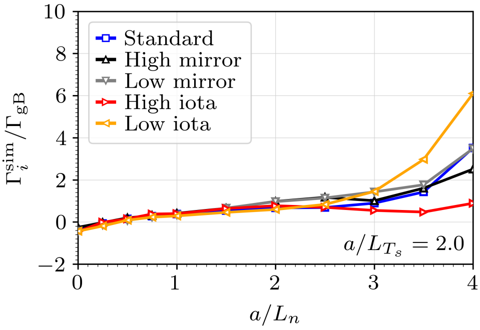


Simulated particle flux ($a/L_{T_s} = 2.0$)



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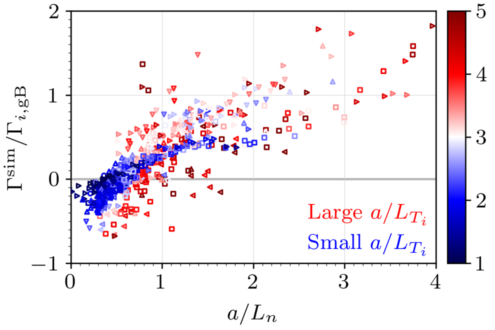
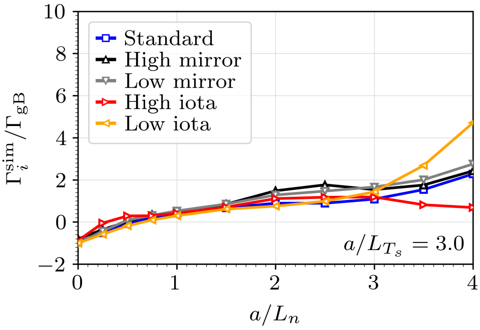
Simulated particle flux



Simulated particle flux ($a/L_{T_s} = 3.0$)

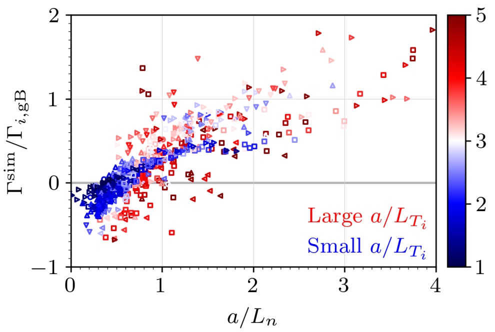


Turbulent particle flux for experimental plasma parameters

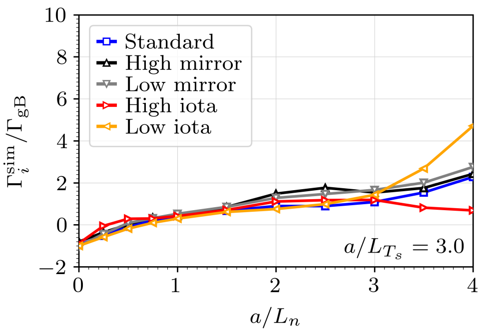
Simulated database of turbulent particle flux for W7-X

A robust turbulent inward convection (particle pinch) is observed in the simulated database, which is mostly independent of the magnetic configuration considering the experimental parameter space. Configuration-dependent effects are expected to emerge for large density gradients.

Simulated particle flux



Simulated particle flux



Overview

Conclusions and future work

A comprehensive database of simulated turbulent transport has been created

- Built using 1340 nonlinear, flux-tube, electrostatic `stella` simulations
  - 2×318 experimental data points from 153 W7-X discharges
  - 5×110 academical data points for five specific W7-X configurations
- This work represents a major computational effort and a significant step forward in the validation of gyrokinetic codes against experimental measurements, providing an extensive nonlinear simulation dataset for W7-X

Qualitative agreement between simulated and experimental W7-X databases

- Clear reduction of turbulent heat transport with density peaking
- Strong dependence of the heat fluxes on the temperature gradients
- A robust simulated inward turbulent particle flux for small density gradients
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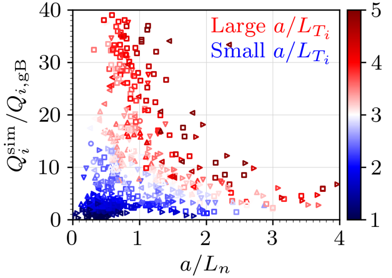
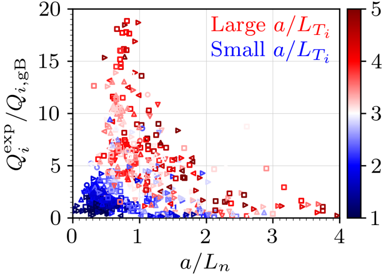
Work in progress and future plans

- Include electromagnetic effects and collisions, perform self-consistent simulations using experimental pressure profiles and correct magnetic equilibria, run multi-scale simulations to include electron-scale contributions





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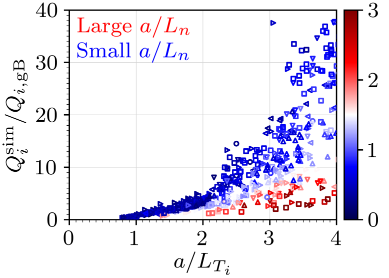

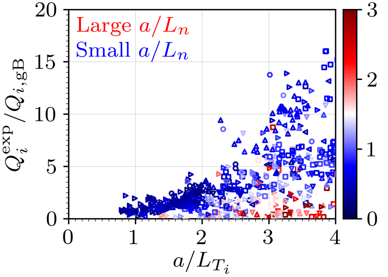

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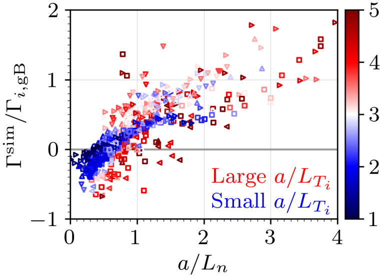

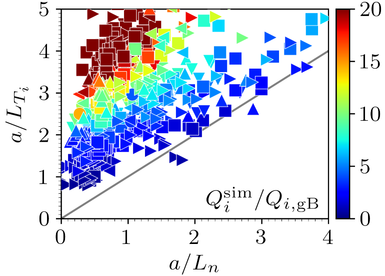

C. D. Beidler, H. M. Smith, A. Alonso, T. Andreeva, J. Baldzuhn, M. N. A. Beurskens, M. Borchardt, S. A. Bozhenkov, K. J. Brunner, H. Damm, et al. Demonstration of reduced neoclassical energy transport in Wendelstein 7-X. *Nature*, 596 (7871):221–226, 2021.

S. A. Bozhenkov, Y. Kazakov, O. P. Ford, M. N. A. Beurskens, J. Alcusón, J. A. Alonso, J. Baldzuhn, Ch Brandt, K. J. Brunner, H. Damm, et al. High-performance plasmas after pellet injections in Wendelstein 7-X. *Nuclear Fusion*, 60(6): 066011, 2020.

M. Wappl, S. A. Bozhenkov, T. Andreeva, S. Bannmann, H. M. Smith, R. C. Wolf, and the W7-X Team. Experimental power balance study on turbulent heat transport at Wendelstein 7-X. *Plasma Physics and Controlled Fusion*, 67(7): 075025, jul 2025. URL `https://doi.org/10.1088/1361-6587/ade824`.

H. Thienpondt, J. M. García-Regaña, I. Calvo, G. Acton, and M. Barnes. Influence of the density gradient on turbulent heat transport at ion-scales: an inter-machine study with the gyrokinetic code stella. *Nuclear Fusion*, 65(1):016062, jan 2025. URL `https://doi.org/10.1088/1741-4326/ad9ab9`.

H. Thienpondt, J. M. García-Regaña, I. Calvo, J. A. Alonso, J. L. Velasco, A. González-Jerez, M. Barnes, K. Brunner, O. Ford, G. Fuchert, J. Knauer, E. Pasch, and L. Vanó. Prevention of core particle depletion in stellarators by turbulence. *Phys. Rev. Res.*, 5:L022053, Jun 2023. doi: 10.1103/PhysRevResearch.5.L022053. URL `https://link.aps.org/doi/10.1103/PhysRevResearch.5.L022053`.