MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Towards first-principles simulations of the L- to H-mode transition with the global gyrokinetic turbulence code GENE-X

GENE-X

TSVV1 Workshop 2024 / H-mode Workshop 2024

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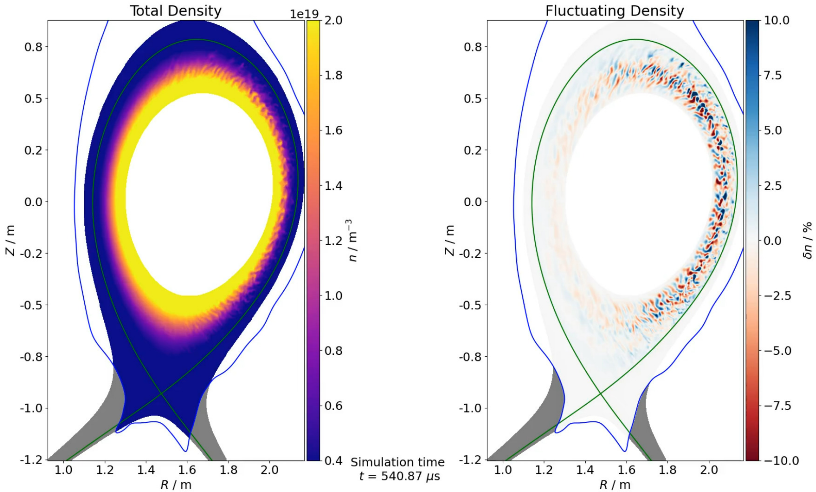
EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Example: Simulation of turbulence in AUG L-mode



In this talk we investigate the transition between turbulent states in AUG by performing a power ramp on an L-mode

Part I

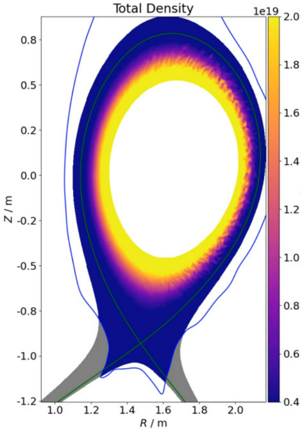
- Overview of the GENE-X code

Part II

- Previous validation studies in AUG and TCV

Part III

- Turbulence simulations in AUG with a power ramp

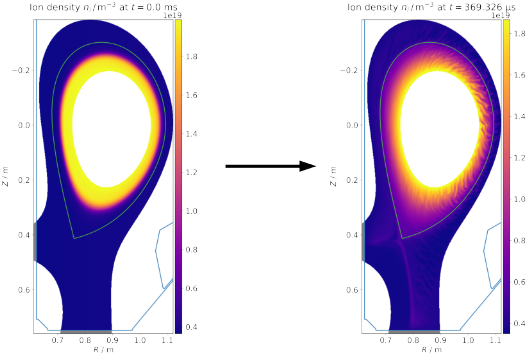


GENE-X Overview

GENE-X enables gyrokinetic turbulence simulations in X-point geometries

Features:

- grid-based (Eulerian)
- global
- non-linear
- full-f
- electromagnetic (EM)
- collisional



GENE-X can simulate from the core to the wall.

Efficiently designed for massively parallelized conventional (CPU-based) supercomputers. Strong scaling with 93% efficiency up to 512 nodes ($\approx$ 20k cores).

[D. Michels, A. Stegmeir, P. Ulbl et al. CPC 264 (2021)] [D. Michels, P. Ulbl et al. PoP 29 (2022)] [P. Ulbl, T. Body et al. PoP 30 (2023)]

GENE-X solves a full-f, collisional, EM gyrokinetic model

evolution | $\mathbf{B}^*$ advection | perpendicular drifts

$$\frac{\partial f_\alpha}{\partial t} + v_{||}\frac{\mathbf{B}^*}{B^*_{||}}\cdot\nabla f_\alpha + \frac{c}{q_\alpha B^*_{||}}\mathbf{b}\times\left(\mu\nabla B + q_\alpha\nabla\phi_1 + \nabla H_2\right)\cdot\nabla f_\alpha$$

$$-\frac{\mathbf{B}^*}{m_\alpha B^*_{||}}\cdot\left(\mu\nabla B + q_\alpha\nabla\phi_1 + \nabla H_2\right)\frac{\partial f_\alpha}{\partial v_{||}} - \frac{q_\alpha}{m_\alpha c}\frac{\partial A_{1,||}}{\partial t}\frac{\partial f_\alpha}{\partial v_{||}} = \sum_\beta C_{\alpha\beta}(f_\alpha, f_\beta)$$

vspace-advection | magnetic induction | collisions

with

$$-\nabla\cdot\left(\sum_\alpha \frac{m_\alpha c^2 n_\alpha}{B^2}\nabla_\perp\phi_1\right) = \sum_\alpha q_\alpha\int f_\alpha\,\mathrm{d}W, \quad -\Delta_\perp A_{1,||} = 4\pi\sum_\alpha\frac{q_\alpha}{c}\int v_{||} f_\alpha\,\mathrm{d}W.$$

$$\mathbf{B}^* = \mathbf{B} + \frac{m_\alpha c}{q_\alpha}v_{||}\nabla\times\mathbf{b} + \nabla A_{1,||}\times\mathbf{b}, \quad H_2 = -\frac{m_\alpha c^2}{2B^2}\left|\nabla_\perp\phi_1\right|^2, \quad \mathrm{d}W = 2\pi B^*_{||}/m_\alpha \mathrm{d}v_{||}\mathrm{d}\mu.$$

Based on [D. Michels, P. Ulbl, W. Zholobenko et al., PoP 29 (2022) 032307].

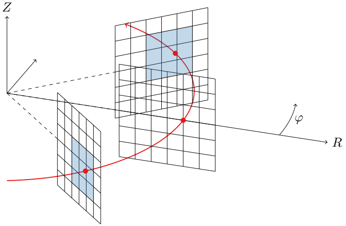
The Flux-Coordinate Independent Approach (FCI) allows for simulations in X-point geometries

Plasma turbulence is field aligned, **but** conventional field aligned coordinates break down at the X-point.

Solution: FCI approach

- Collection of Cartesian poloidal planes.
- Connected with magnetic field lines.

$\rightarrow$ **locally field aligned coordinates.**



Discretization:

$\perp$

- 4th order sym. FD for $x, z, v_{||}$ derivatives
- 2nd order Arakawa for non-linear terms
- 2nd order elliptic solvers (GMRES + multigrid))

$||$

- Field line tracing
- Bicubic interpolation
- 4th order sym. FD for y

[D. Michels, A. Stegmeir, P. Ulbl et al., CPC 264 (2021) 107986]

Collision models of varying fidelity are available in GENE-X

Bhatnagar-Gross-Krook (BGK)

$$C_{\alpha\beta} = \nu_{\alpha\beta}\left(\frac{B}{B_{||}^*}\mathcal{M}_{\alpha\beta} - f_\alpha\right).$$

Lenard-Bernstein/Dougherty (LBD)

$$C_{\alpha\beta} = \frac{\nu_{\alpha\beta}}{B_{||}^*}\left\{\frac{\partial}{\partial v_{||}}\left[\left(v_{||} - u_{||,\alpha\beta}\right)B_{||}^* f_\alpha + \frac{1}{2}v_{\mathrm{th},\alpha\beta}^2 \frac{\partial B_{||}^* f_\alpha}{\partial v_{||}}\right] + \frac{\partial}{\partial \mu}\left[2\mu B_{||}^* f_\alpha + \frac{m_\alpha v_{\mathrm{th},\alpha\beta}^2}{B}\mu\frac{\partial B_{||}^* f_\alpha}{\partial \mu}\right]\right\}.$$

- Conservative finite volume discretization (2nd order)

[P. Ulbl, D. Michels and F. Jenko, Contrib. Plasma Phys. 2021, e202100180]

Fokker-Planck/Landau (FPL)

$$C_{\alpha\beta} = -\frac{1}{B_{||}^*}\frac{\partial}{\partial \mathbf{v}}\cdot\left[B_{||}^*\left(\mathbf{E}_{\alpha\beta}f_\alpha + \mathbf{D}_{\alpha\beta}\cdot\frac{\partial}{\partial \mathbf{v}}f_\alpha\right)\right],$$

$$\mathbf{E}_{\alpha\beta} = \frac{\Gamma_{\alpha\beta}}{m_\beta}\int \mathrm{d}\mathbf{v}'\,\mathbf{U}_{\alpha\beta}^{\mathrm{E}}\cdot\frac{\partial}{\partial \mathbf{v}'}f_\beta',$$

$$\mathbf{D}_{\alpha\beta} = -\frac{\Gamma_{\alpha\beta}}{m_\alpha}\int \mathrm{d}\mathbf{v}'\,\mathbf{U}_{\alpha\beta}^{\mathrm{D}}f_\beta',$$

$$\mathbf{U}_{\alpha\beta}^{\mathrm{E}} = \begin{pmatrix} U_{\perp,\perp} & U_{\perp,||} \\ U_{||,\perp} & U_{||,||}\end{pmatrix},\quad \mathbf{U}_{\alpha\beta}^{\mathrm{D}} = \begin{pmatrix} U_{\perp,\perp} & U_{\perp,||} \\ U_{\perp,||} & U_{||,||}\end{pmatrix}.$$

- Components of **U** are given by linear combinations of elliptic integrals $E(m)$, $K(m)$
- 2nd order FV discretization

See [R. Hager et. al, JCP315 (2016)]

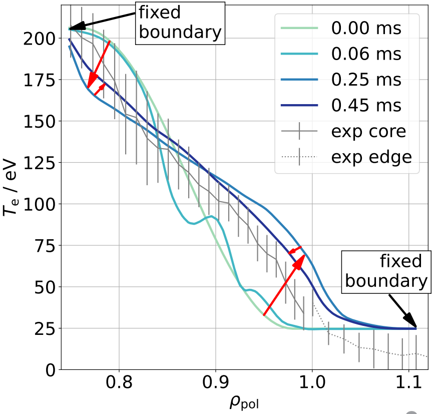
Boundary conditions provide heat and particle fluxes in our simulations

"First-principles" modelling: we start from an arbitrary initial state, not imposing the experimental profiles as a whole.

GENE-X BCs

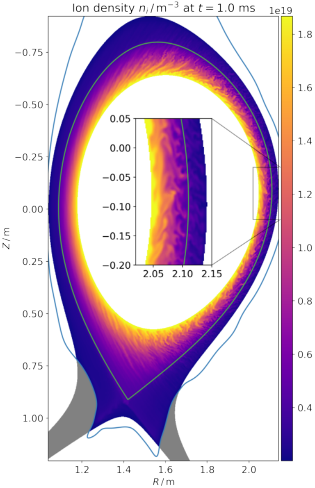
Dirichlet with

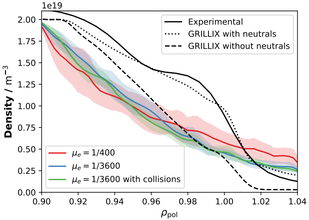
- **Distribution function**: Maxwellian with experimental profile values for n and T (no flow)
- **Potentials**: zero

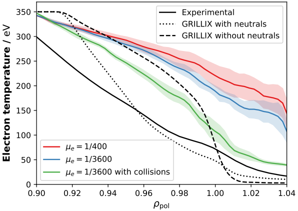


Previous Validation Studies with GENE-X

ASDEX Upgrade Simulations show that realistic mass ratio and collisions are required



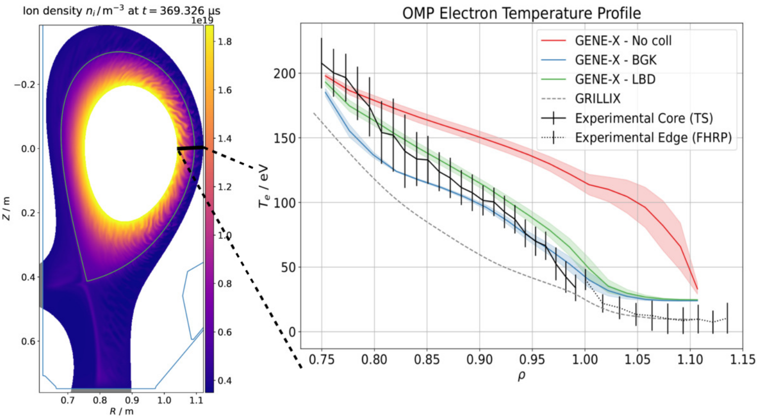




- Reduced/realistic mass ratio and BGK coll.
- Electron cooling by collisions
- SOL fall-off length λ_q broadened by collisions
- Case where neutrals are important, electron temperature set too high

[D. Michels, P. Ulbl, W. Zholobenko et al., Phys. Plasma 29 (2022) 032307]

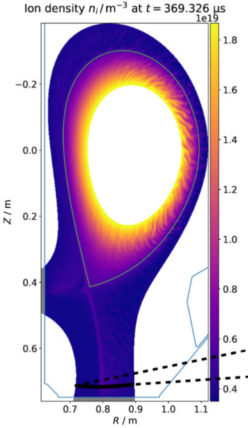
Simulation with LBD collisions reproduces experimental electron temperature profile in TCV-X21

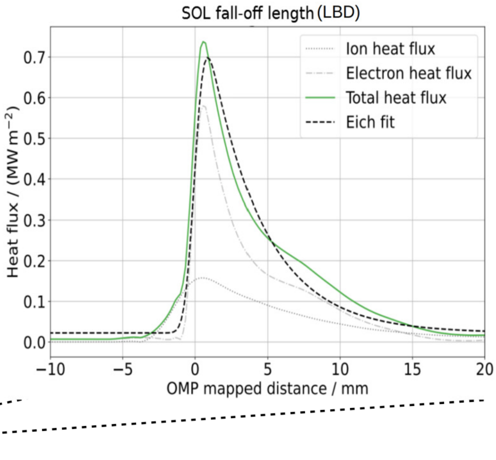


- Realistic T_e profile reproduced by global *collisional* gyrokinetic simulations
- Collisional de-trapping of trapped electrons in the SOL is essential
- Results and data published open access

[P. Ulbl et al. PoP 30 (2023)]
[Data: 10.5281/zenodo.7894731]

Collisional simulations develop "lambda-q" close to experiment





- Divertor heat flux fall-off follows Eich-fit function
- SOL fall-off length λ_q
  Experimental: **5.5 mm***

Fluid Models*	
GRILLIX	1.1 mm

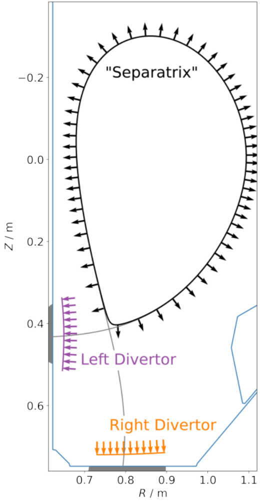
*[D. S. Olivera, T. Body et al. NF 62 (2022)]

GENE-X (Gyrokinetic)	
No Coll	1.34 mm
Coll BGK	**4.68 mm**
Coll LBD	**3.75 mm**

[P. Ulbl et al. PoP 30 (2023)]
[Data: `10.5281/zenodo.7894731`]

A consistent power balance is only achieved using LBD

Q_r / kW	Exp	No Coll	BGK	LBD
Separatrix	120	394	35.6	131.5
Both Divertors	-	136.5	48.8	135.6
Right Divertor	38.1	101.3	51.6	68.6
Left Divertor	-	35.2	-2.8	67.0



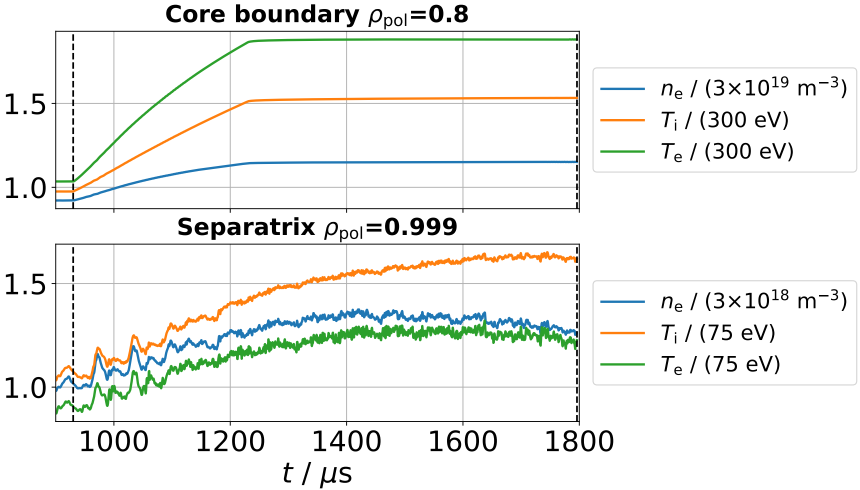
Takeaways

- Separatrix power matches experiment within 10%
- LBD simulation has consistent power balance
- No neutrals and radiation yet

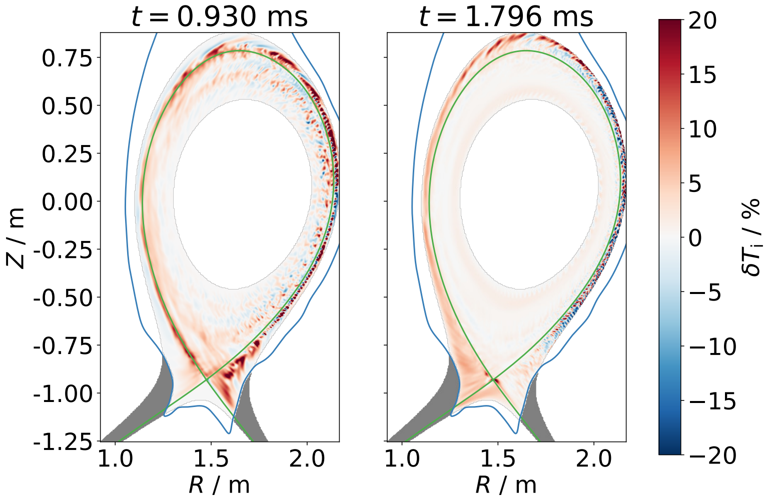
[P. Ulbl et al. PoP 30 (2023)]

Turbulence simulations with a power ramp

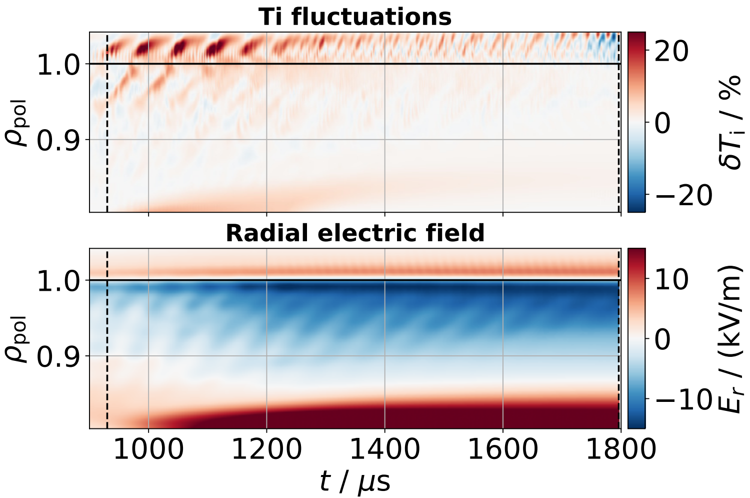
We implement a power ramp by adjusting the inner BCs



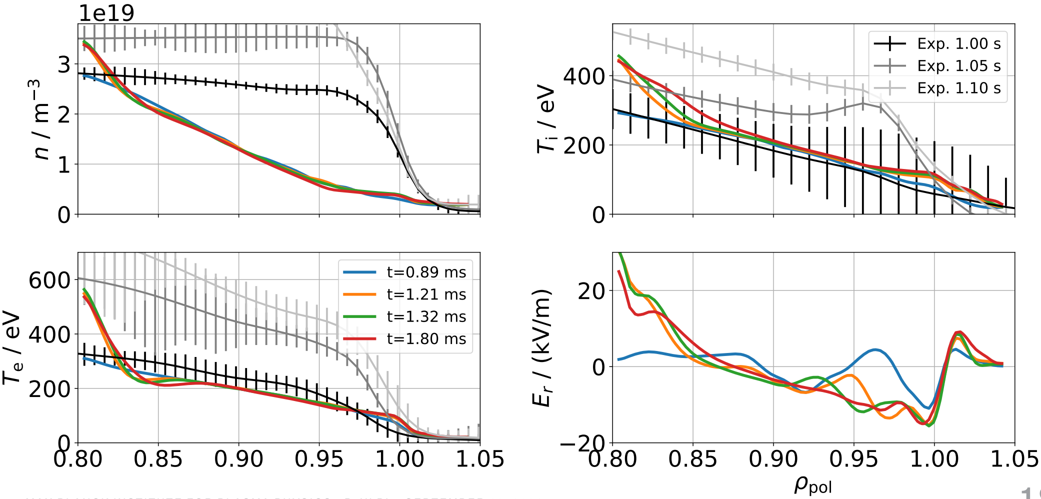
We observe a transition into a turbulence-suppressed state



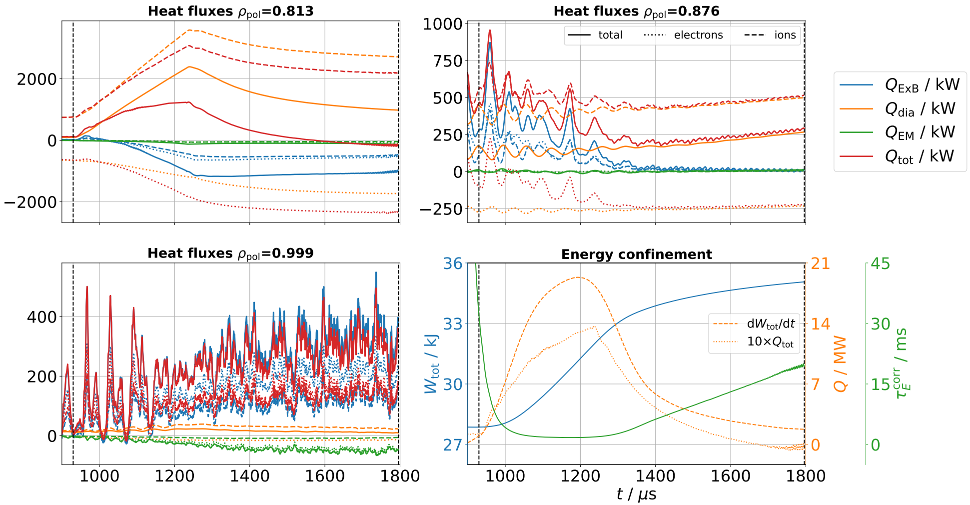
Fluctuations within $\rho < 1$ are suppressed, E_r well builds up



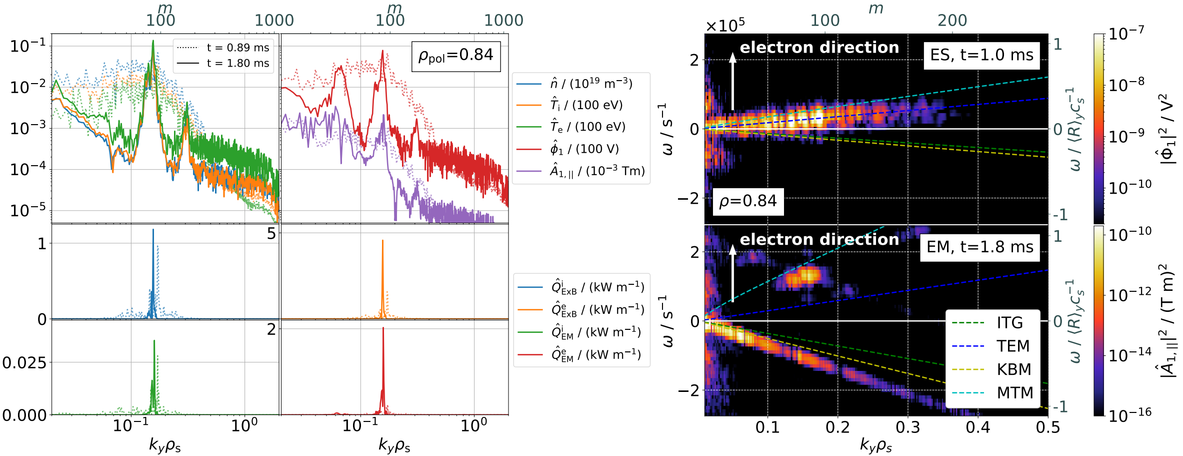
Low density regime due to missing neutral gas particle source close to the separatrix → H-mode highly unlikely



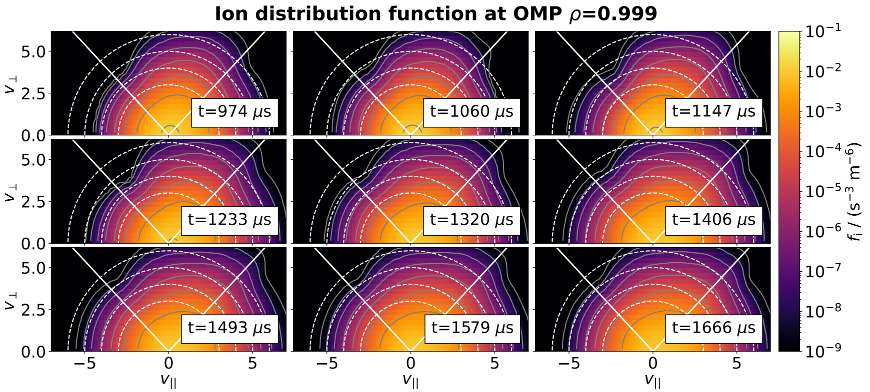
Transport changes locally - NEO and EM become important

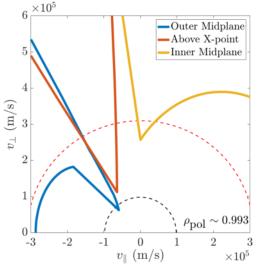


Turbulence characteristics change locally - TEM to MTM/KBM?



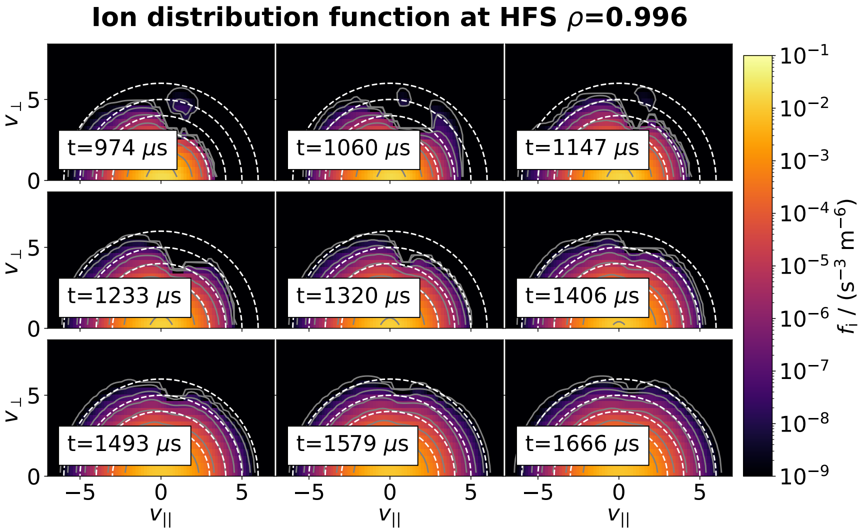
Indications for ion orbit losses (IOL) close to separatrix →diagnostic capabilities are required

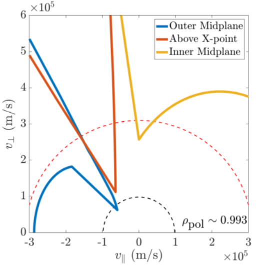




[R. Brzozowski, PhD Thesis]

Shape of loss region at HFS differs to LFS in line with theory





[R. Brzozowski, PhD Thesis]

Summary & Outlook

Low-density turbulence simulations with power ramp show transition into turbulence-suppressed state

Key Takeaways

- Fluctuations in confined region mostly suppressed, while SOL scales become smaller
- E_r-well build-up, outer shear increases
- Transport and turbulence change locally, EM and NEO effects become important
- IOL dynamics observed (further analysis required)

Next steps

- Implement heat and particle sources (partially completed)
- Repeat simulations with core heat source and separatrix particle source
- Diagnostics for IOL (who does the work?)
- **Why is turbulence suppressed in the current case?**

Contact

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