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

TSVV4/1 Workshop 2024 / H-mode Workshop 2024

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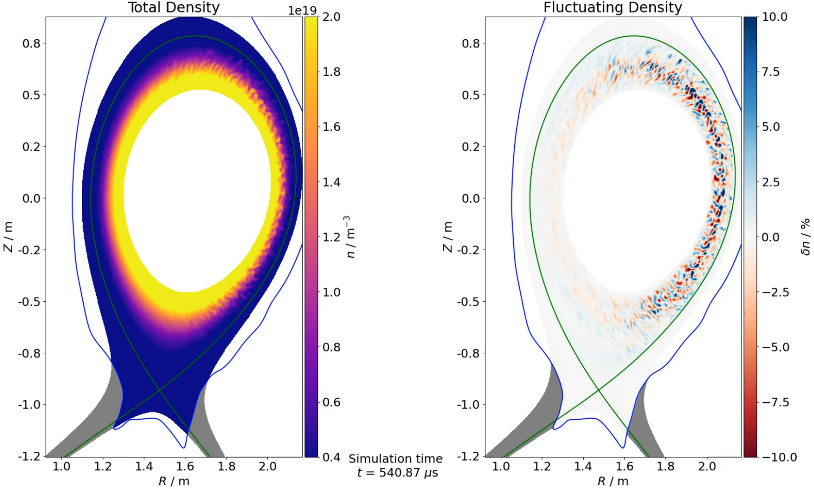
Example: Simulation of turbulence in AUG L-mode



Simulation time
$t = 540.87\ \mu s$

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

Part I

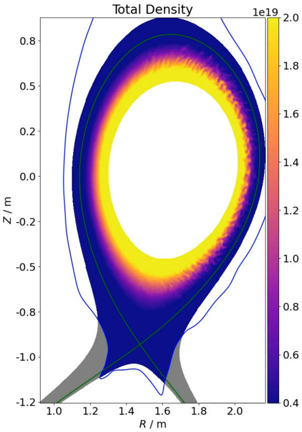
- Overview of the GENE-X code

Part II

- Previous validation studies in AUG and TCV

Part III

- Turbulence simulations in AUG with a power ramp

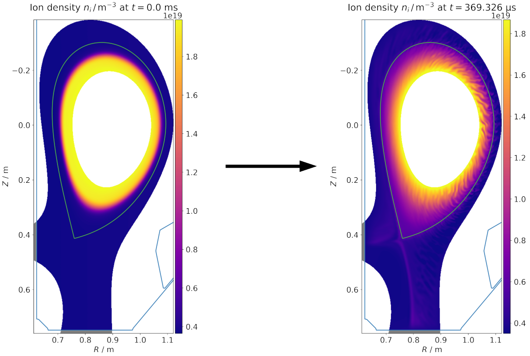


GENE-X Overview

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

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

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

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].

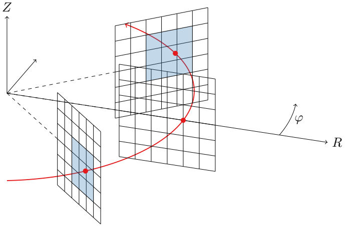
The Flux-Coordinate Independent Approach (FCI) allows for simulations in X-point geometries

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.

→ **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)]

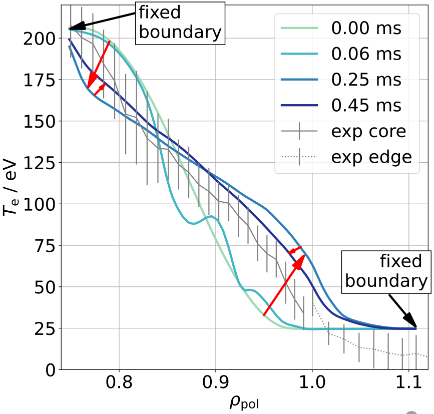
Boundary conditions provide heat and particle fluxes in our simulations

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

GENE-X BCs

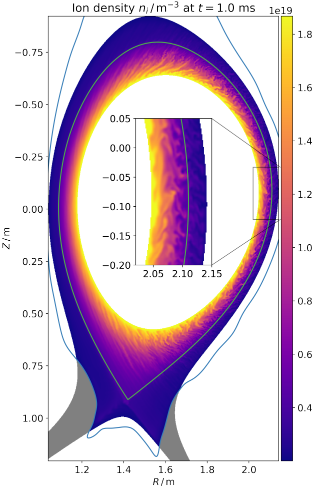
Dirichlet with

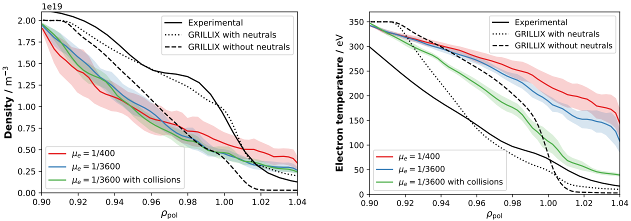
- **Distribution function**: Maxwellian with experimental profile values for n and T (no flow)
- **Potentials**: zero



Previous Validation Studies with GENE-X

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

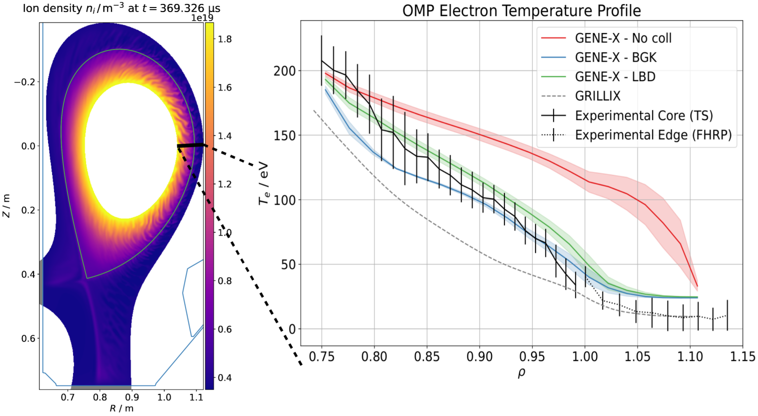




- Reduced/realistic mass ratio and BGK coll.
- Electron cooling by collisions
- SOL fall-off length λ_q broadened by collisions
- Case where neutrals are important, electron temperature set too high

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

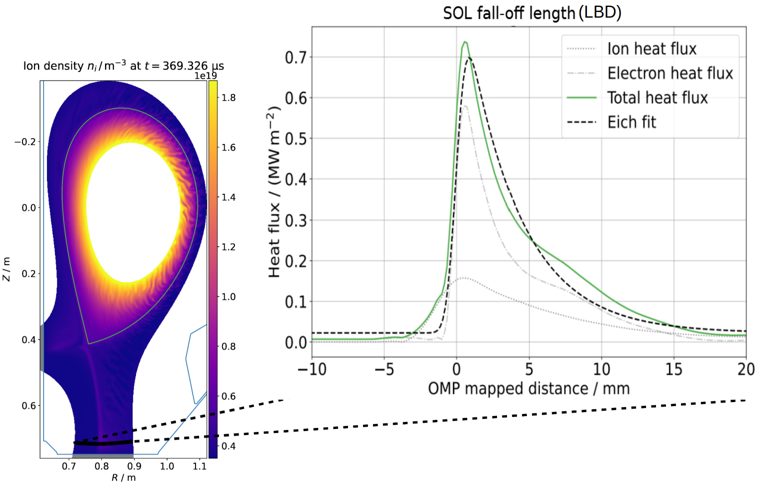
Simulation with LBD collisions reproduces experimental electron temperature profile in TCV-X21



- 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)]

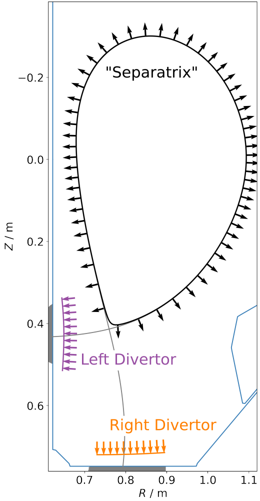
GENE-X (Gyrokinetic)	
No Coll	1.34 mm
Coll BGK	**4.68 mm**
Coll LBD	**3.75 mm**

[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



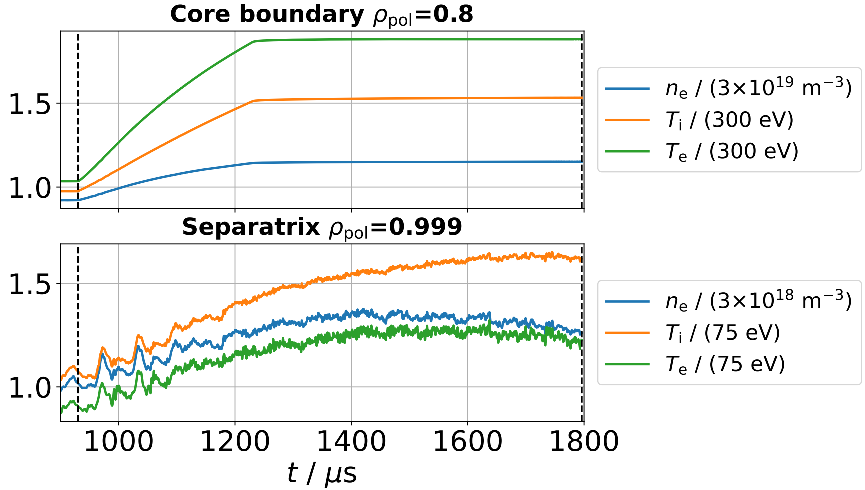
Takeaways

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

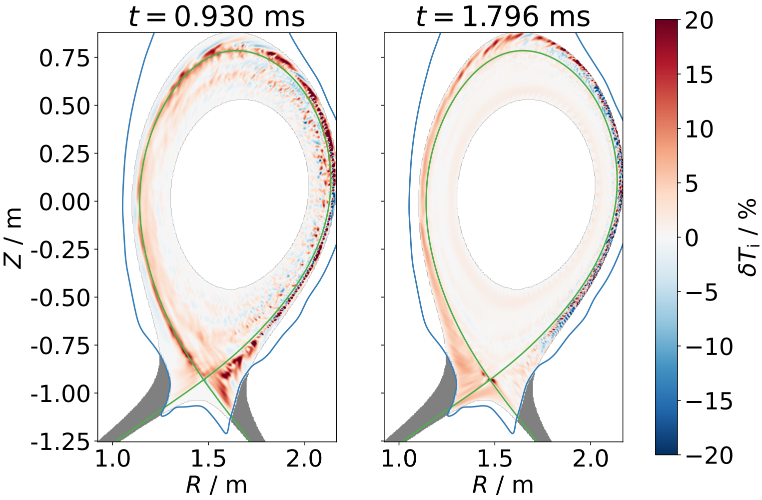
[P. Ulbl et al. PoP 30 (2023)]

Turbulence simulations with a power ramp

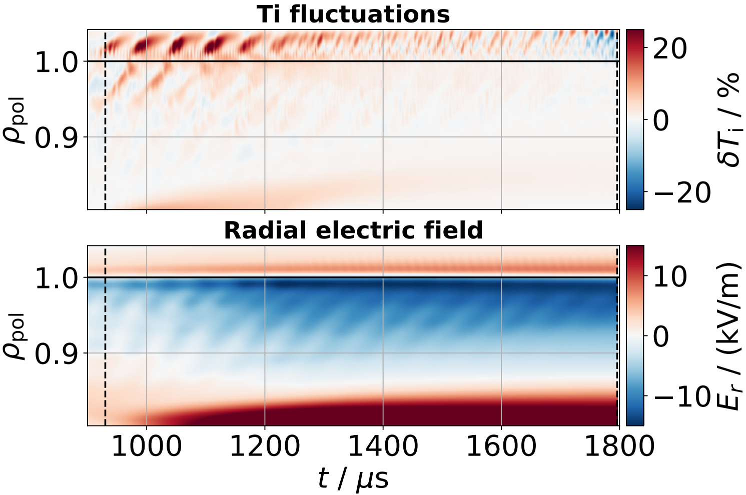
We implement a power ramp by adjusting the inner BCs



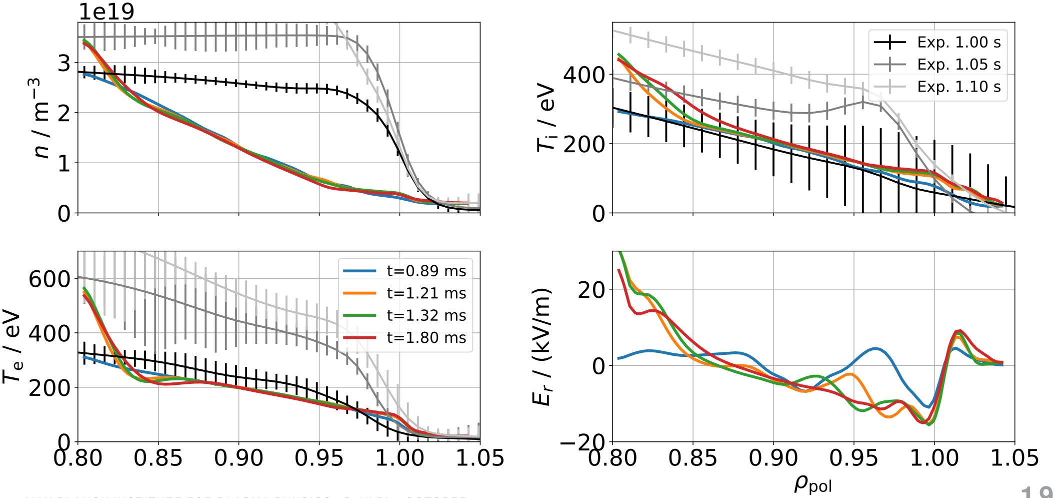
We observe a transition into a turbulence-suppressed state



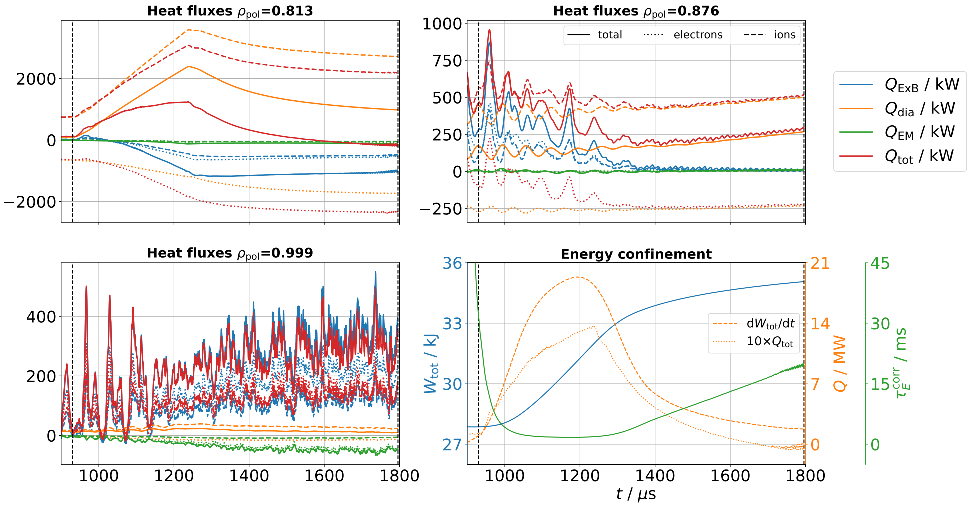
Fluctuations within $\rho < 1$ are suppressed, E_r well builds up



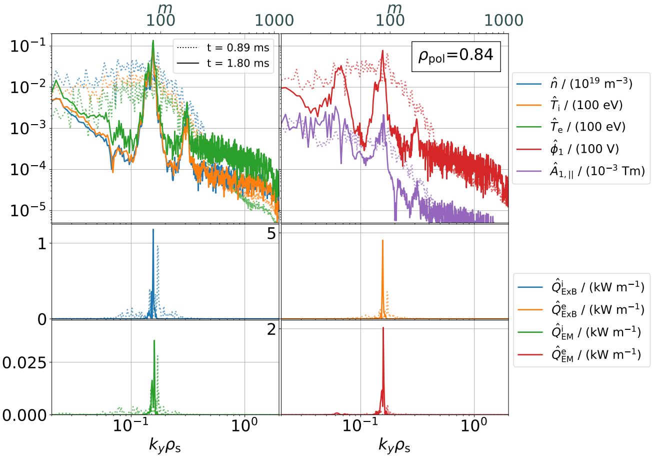
Low density regime due to missing neutral gas particle source close to the separatrix → H-mode highly unlikely

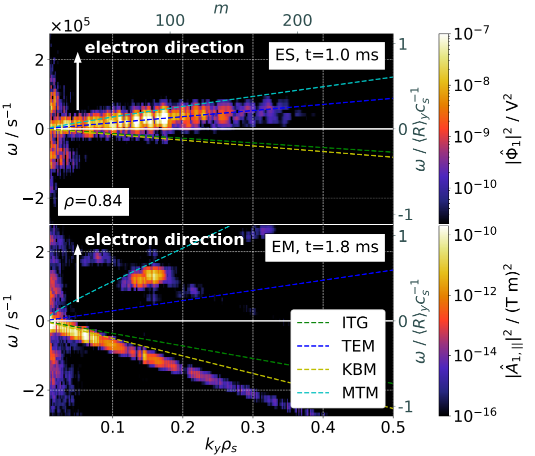


Transport changes locally - NEO and EM become important

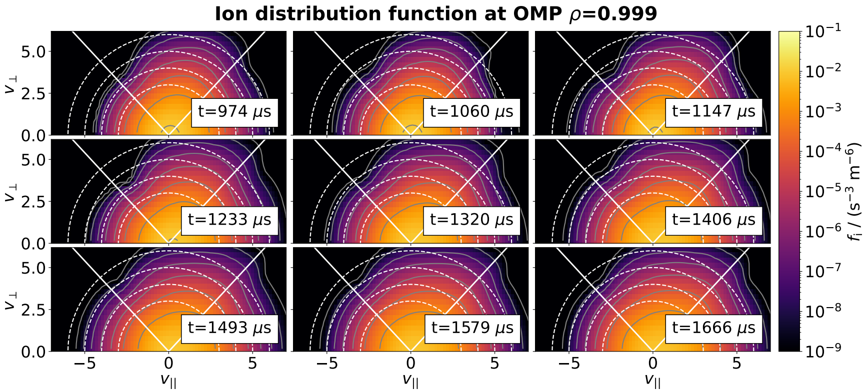


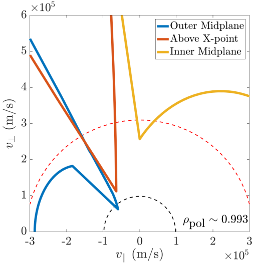
Turbulence characteristics change locally - TEM to MTM/KBM?





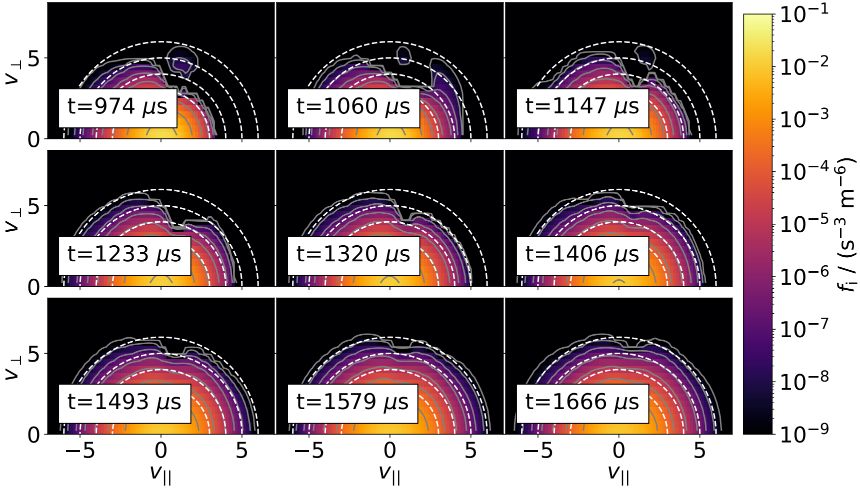
Indications for ion orbit losses (IOL) close to separatrix →diagnostic capabilities are required



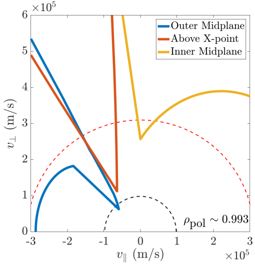


[R. Brzozowski, PhD Thesis]

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



Ion distribution function at HFS ρ=0.996



[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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