Gyrokinetic Simulations of Turbulent Energy Exchange in a Dipole Configuration

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Outline

Planetary magnetospheres and levitated ring dipole devices confine high-temperature plasma in strongly inhomogeneous magnetic fields.

Entropy-mode turbulence, driven by magnetic curvature and pressure gradients, can produce an inward particle pinch, in which particles are transported against density gradients. [Kobayashi+ (2009, 2010)]

Recent Z-pinch simulations showed that entropy-mode turbulence can also drive collisionless thermal equilibration between species. [Numata (2025)]

This work extends the study of turbulent energy exchange to three-dimensional dipole geometry.

Key question: Does the collisionless energy-exchange mechanism persist in dipole plasmas?

Answer: Yes. The mechanism persists, but particle flux and inter-species energy exchange decrease as the flux-tube location (ϱ_{fl}) increases.

These results may help explain temperature profiles and self-organization in magnetospheric and laboratory dipole plasmas, including RT-1.

Main findings: Collisionless turbulent energy exchange persists in dipole geometry, but both particle flux and energy exchange decrease as the flux tube moves outward.

Acknowledgements

This work is supported by JST [Moonshot R&D Program] Grant Number [JPMJMS25A6]. The computation of this work is performed on SQUID at D3 Center, The University of Osaka and on the 'Plasma Simulator' of NIFS with the support and under the auspices of the NIFS Collaboration Research program (NIFS25KISM016).

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

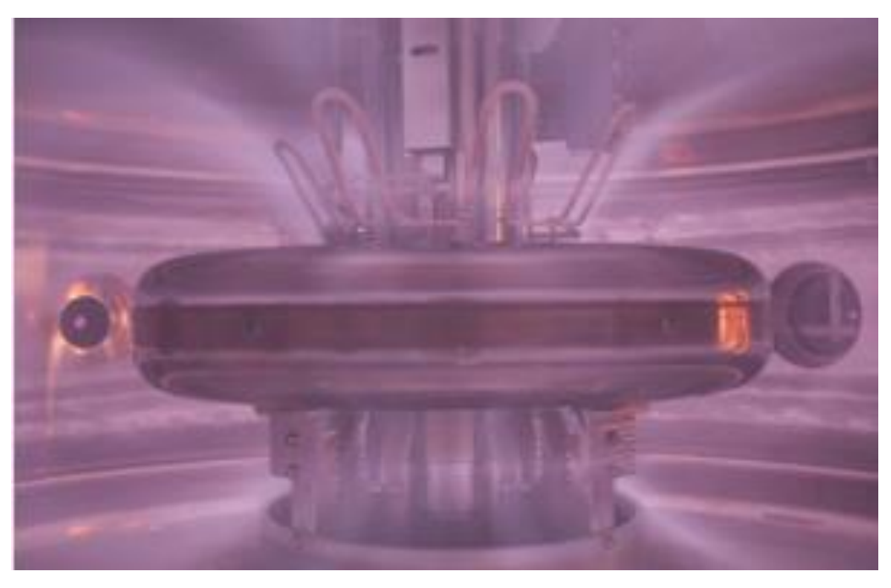
RT-1 Upgrade Plan

Present Status:
Electron bulk 10eV + small fraction of 10kev
Ions are about 10~100eV [Nishiura (2017)]

Target:
Increase ion temperature to 1kev

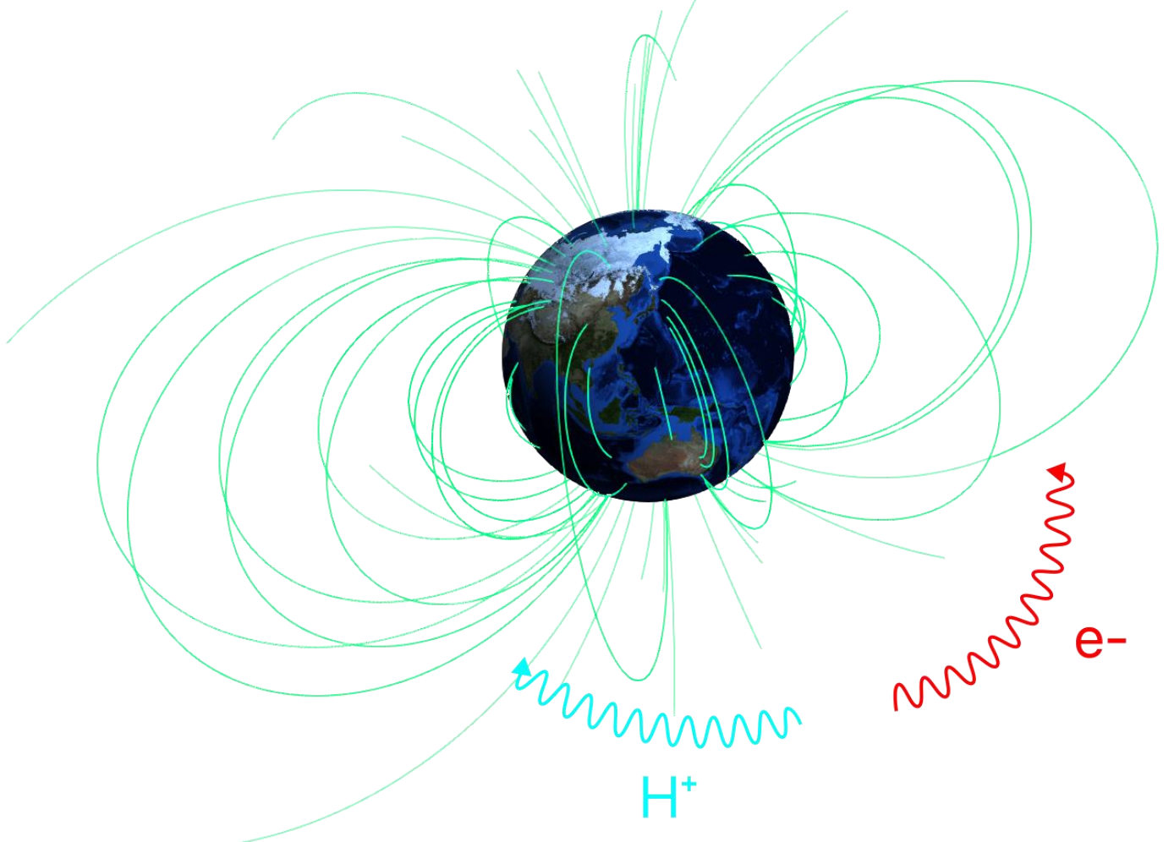
Replace a HTC ring coil and install new ECH system to increase density and increase bulk electron and ion temperature by collisional relaxation.

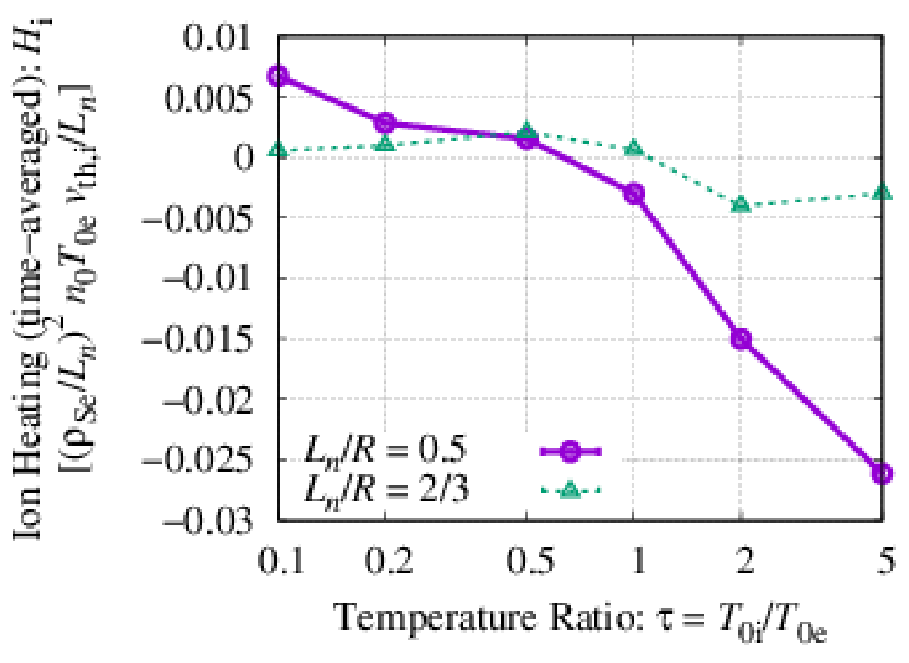
Explore other ion heating mechanisms.



RT-1 Project
[https://www.ppl.k.u-tokyo.ac.jp/]

Turbulent Thermal Equilibration





Collisionless energy exchange between species was found in the Z-pinch limit [Numata (2025)].

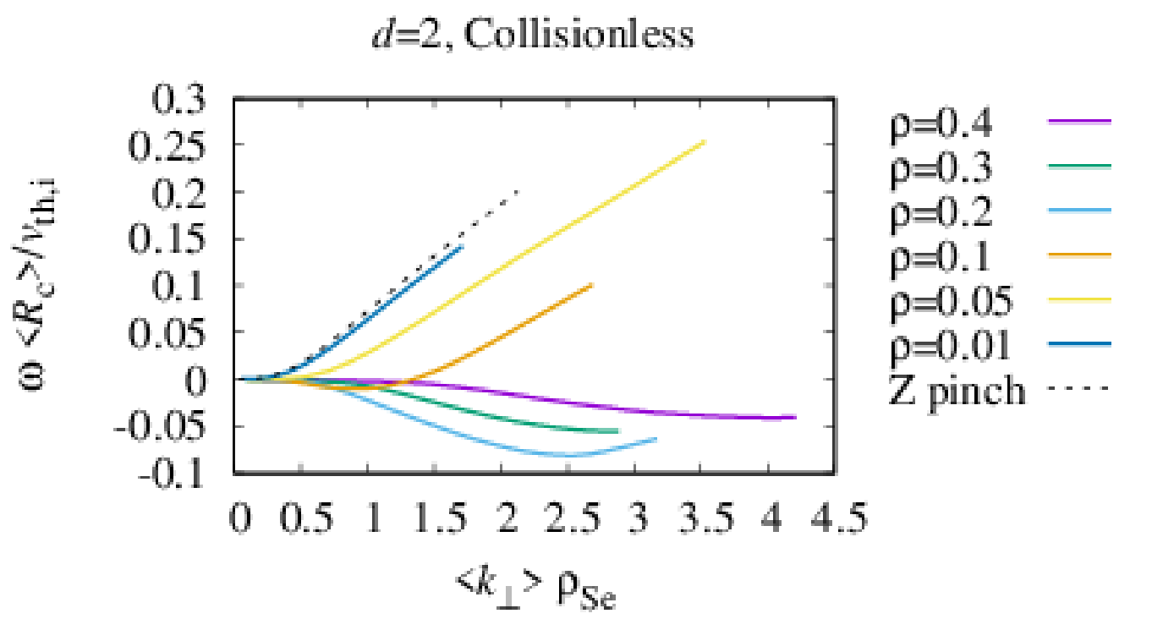
In a Z-pinch, entropy-mode turbulence is driven by magnetic curvature and pressure gradients.

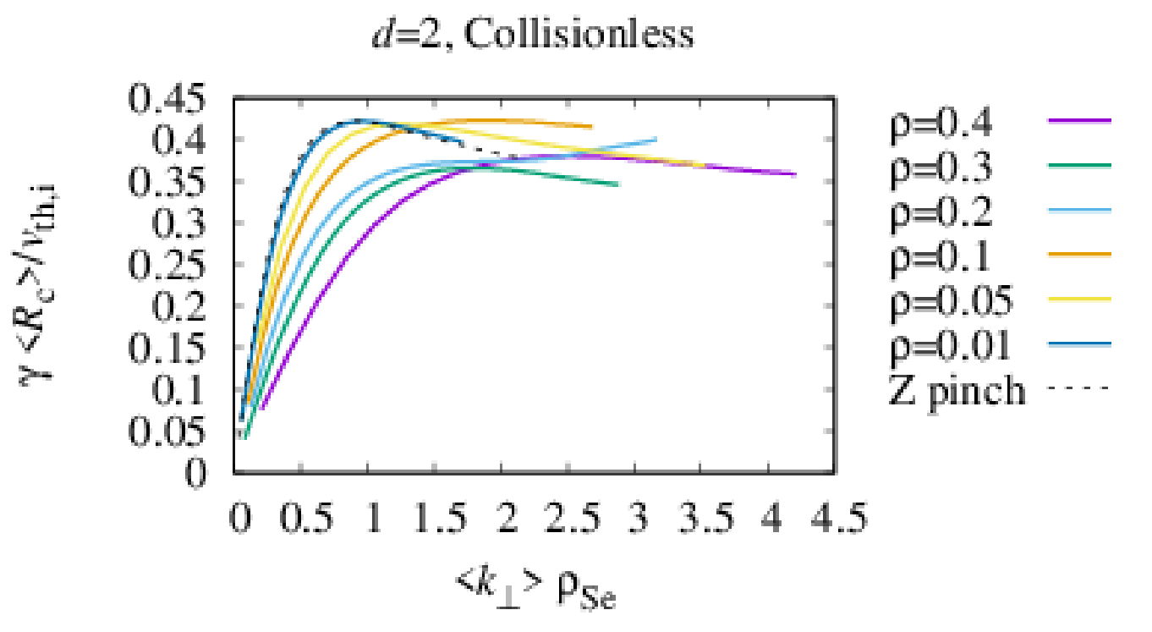
When the temperature ratio ($\tau = Ti/Te$) ≠ 1, wave-particle resonances allow one species to carry negative energy. This species feeds the instability using free energy from the background.

The resulting turbulence drives nonlinear energy exchange between species. The hotter species is cooled and the colder species is heated, leading toward thermal equilibration.

Key question: Does this mechanism persist in dipole plasmas, where field-line variation and particle trapping are important.

Linear Stability (entropy mode)





Linear simulations were performed for several flux-tube locations, ϱ_{fl}. As $\varrho_{\mathrm{fl}} \to 0$, the eigenvalues approach the Z-pinch limit. The sign change of the real frequency suggests a change in the dominant resonant species and in the direction of collisionless energy flow. The growth rate varies only weakly with ϱ_{fl}.

Gyrokinetic Sim. of Dipole Plasmas

Local electrostatic gyrokinetic equations for non-Boltzmann part h_s of the distribution function $\delta f_s = -(q_s\phi/T_{0s})f_{0s} + h_s$

$$\frac{\partial h_s}{\partial t} + \left(v_\parallel \boldsymbol{b} + \boldsymbol{v}_{\mathrm{D},s} + \boldsymbol{v}_{E,s}\right)\cdot\nabla h = \left(\frac{\partial\langle\phi\rangle_{\boldsymbol{R}_s}}{\partial t} + \boldsymbol{v}_{*,s}^{\mathrm{T}}\cdot\nabla\langle\phi\rangle_{\boldsymbol{R}_s}\right)\frac{q_s f_{0s}}{T_{0s}} + C(h_s),$$

$$\sum_s q_s \delta n_s = 0\,,$$

where $\delta n_s = \int \delta f_s \mathrm{d}\boldsymbol{v}$ are solved in a given flux-tube. The dipole magnetic field in (R,ϕ,Z) is given by

$$\Psi = -\frac{1}{2\pi}\frac{4R}{\sqrt{(1+R^2)+Z^2}}\frac{(2-m)K(m)-2E(m)}{m} \qquad m = \frac{4R}{(1+R^2)+Z^2}$$

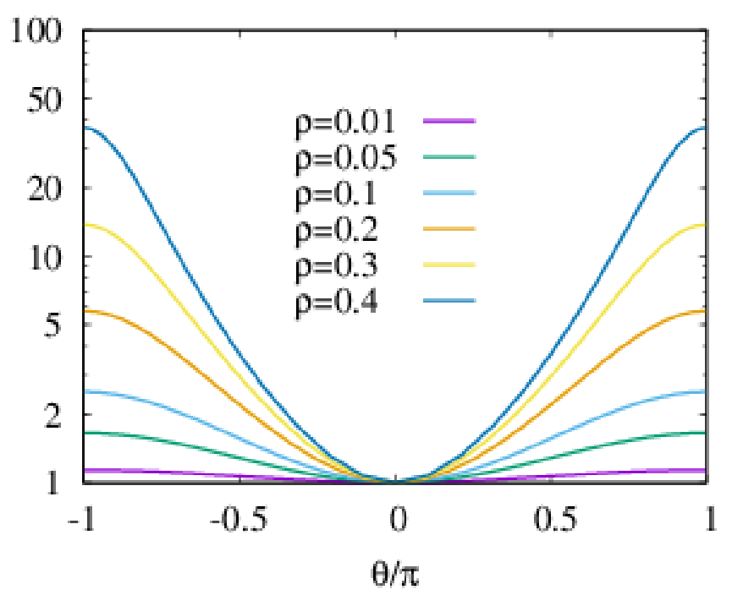
For a given equilibrium magnetic field $B = \nabla\alpha\times\nabla\Psi$, we pick up a field-line of interest specified by ϱ_{fl} and construct the field-line following coordinate ($\rho = 1-R, \alpha = -\phi, \theta$). Then, transform the coordinate into the local flux tube coordinate (x,y,θ) used in GS2.

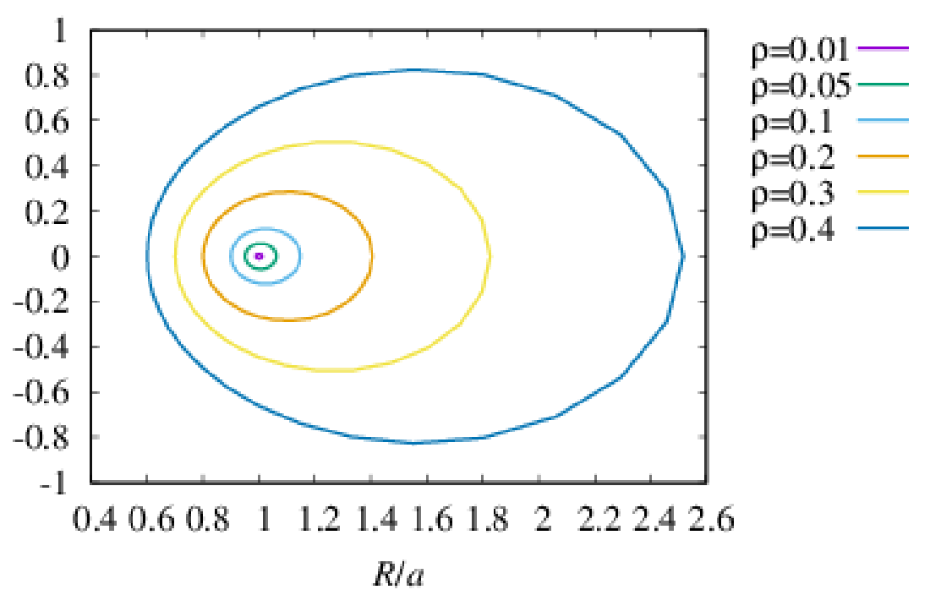
Drifts:

$$\omega_{D,s} = \omega_{\kappa,s}\frac{v_\parallel^2}{v_{\mathrm{th},s}^2} + \omega_{\nabla B,s}\frac{v_\perp^2}{v_{\mathrm{th},s}^2}, \qquad \omega_{*,s}^{\mathrm{T}} = \omega_{*,n,s}\left(1+\eta_s\left(\frac{v^2}{v_{\mathrm{th},s}^2}-\frac{3}{2}\right)\right)$$

$$\omega_{\kappa,s} = \frac{2k_yT_{0s}}{q_s\mathrm{R}L_NB_N}, \qquad \omega_{\nabla B,s} = \frac{2k_yT_{0s}}{q_sl_BL_NB_N}, \qquad \omega_{*,n,s} = \frac{k_yT_{0s}}{q_sl_{n,s}L_NB_N}$$

R: curvature radius
l_B, l_n: scale of B and n
All in ϱ coordinate



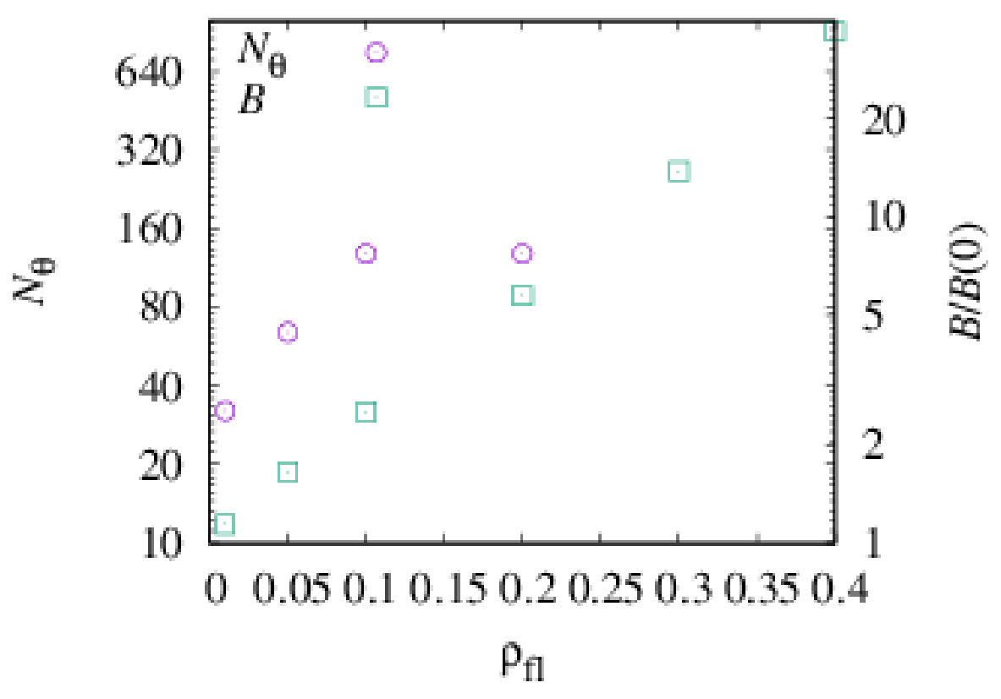


$$d_s = \left\langle 4\frac{\omega_{*,n,s}+\omega_{*,T,s}}{\omega_{\nabla B,s}+\omega_{\kappa,s}}\right\rangle_\theta$$

$$\Rightarrow \frac{\mathrm{R}}{l_{n,s}} \quad as\ \varrho_{\mathrm{fl}} \to 0 \text{ and ES}$$

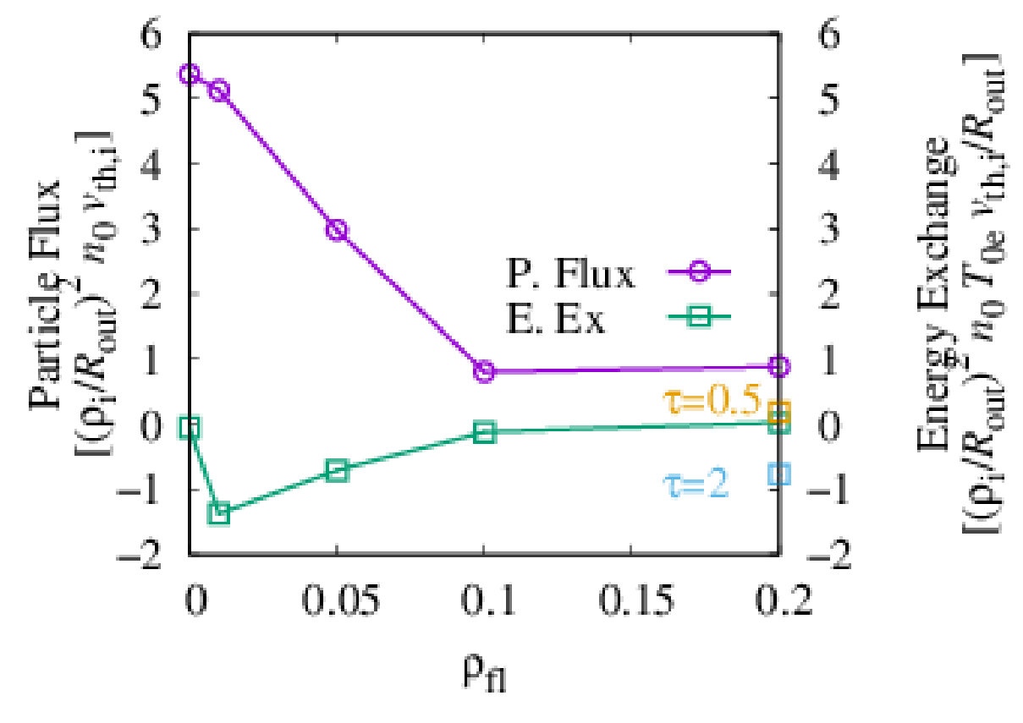
Nonlinear Transport analyses

Parameters are chosen such that turbulence at the outboard midplane matches the Z-pinch limit [Numata (2025)]



Numerical resolution along θ

The required number of grid points along the field line increases as $\varrho_{\mathrm{fl}} \to 0$ and the variation of B increases. Otherwise, the simulation becomes unstable. Numerical dissipation may reduce the required grid size.



For fixed $d_s = 2$, both the particle flux and inter-species energy exchange decrease as ϱ_{fl} increases. At $\varrho_{\mathrm{fl}} = 0.2$, ions are cooled for $\tau = 2$ and heated for $\tau = 0.5$, consistent with turbulent thermal equilibration in the Z-pinch limit.

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52nd EPS Conference on Plasma Physics, Edinburgh, Scotland, 29 June–3 July (2026)