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Energetic particle nonlinear equilibria and transport processes In burning plasmas

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ABSTRACT

- We introduce a theoretical framework to describe transport in the phase space based of the theory of Phase Space Zonal Structures (PSZS) [1-5]
- we extend the usual definition of plasma equilibrium in the presence of a residual level of electromagnetic fluctuations, i.e., the Zonal State (ZS)
- governing equations are derived by means of Gyrokinetic transport theory
- as a simple application, we describe ZS evolution in the absence of symmetry breaking fluctuations
- we calculate PSZS induced by a TAE on the Divertor Tokamak Test (DTT) using DAEPS [6]
- This theoretical approach is consistent with a mixed full-f/delta-f algorithm

BACKGROUND

- Predicting the dynamics of a burning plasma over long time scales, i.e., comparable with the energy confinement time or even longer, is essential to understand next generation fusion experiments
- most of the works for the study of core plasma transport are based on a systematic separation of scales between the reference equilibrium and fluctuations
- energetic particle (EP) transport in fusion devices is a spatiotemporal multi-scale process
- spatio-temporal mesoscales can be observed even in drift wave plasma turbulence simulations
- in a recent work [2] we have emphasized the fundamental importance of the self-consistency of the adopted description, including the determination of the characteristic spatiotemporal scales of the reference state

PHASE SPACES ZONAL STRUCTURES (PSZS)

- PSZS equation is connected with the macro- meso-scopic component unperturbed orbit-averaged distribution function:

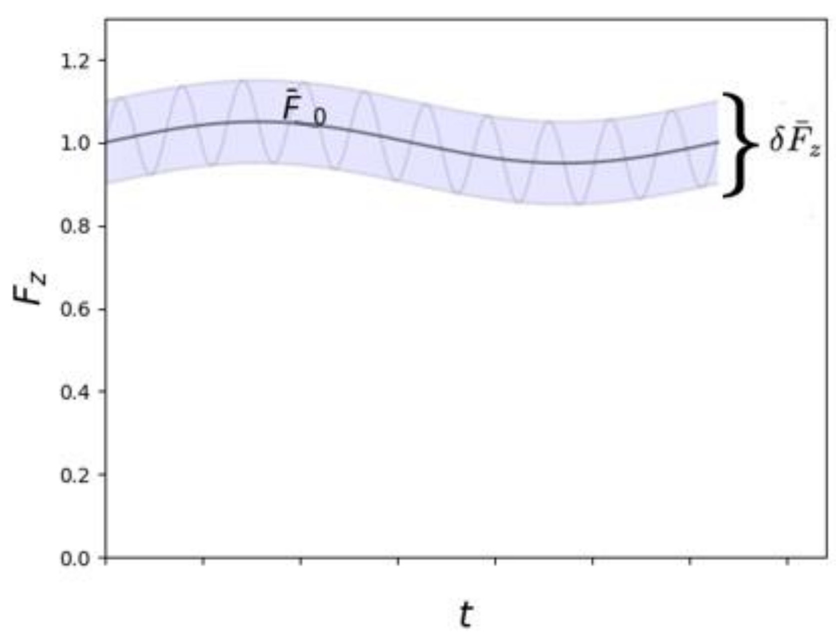
$$\partial_t\left(\overline{e^{iQ_z}\bar{F}_0} \quad +\overline{e^{iQ_z}\delta F_z}\right) = -\frac{1}{\tau_b}\frac{\partial}{\partial\psi}\left[\tau_b\overline{e^{iQ_z}\delta\dot{\psi}\delta F}\right]_z - \frac{1}{\tau_b}\frac{\partial}{\partial\mathcal{E}}\left[\tau_b\overline{e^{iQ_z}\delta\dot{\mathcal{E}}\delta F}\right]_z + \overline{\left(\sum_b C_b^g[F,F_b]+\mathcal{S}\right)_{zS}}$$

- on the LHS we have separated slow and fast spatio-temporal responses

- we can decompose the toroidally symmetric distribution function

$$F_z = \overline{F_{z0}} + \overline{\delta F_z} + \delta\tilde{F}_z$$

- micro-scales are accounted by $\overline{\delta F_z}$ while macro- & meso-scales are described by PSZS



Equilibrium orbit averaged distribution

ZONAL STATE (ZS)

- Computing the ZS dynamics require equations for the zonal field structures (ZFS), i.e., the long-lived component of toroidal symmetric fields
- assume, for simplicity, that ZS is characterized predominantly by the scalar potential $\delta\phi_z$
- we can study its self-consistent evolution in the absence of symmetry breaking fluctuations
- the scalar ZFS is obtained substituting the orbit averaged distribution function into the quasi-neutrality condition:

$$\sum_s \left\langle \frac{e^2}{m}\frac{\partial F_{z0}}{\partial\mathcal{E}}\right\rangle_v \delta\phi_z + \sum_s \left\langle e\hat{I}_0\delta G_z\right\rangle_v = 0$$

$$(\partial_t + \omega_b\partial_{\vartheta_c})\delta G_B = -e^{-iQ_z}\left[\frac{e}{m}\frac{\partial F_{z0}}{\partial\mathcal{E}}\hat{I}_0\partial_t\delta\phi_z + NL\right]$$

- substituting the f component into the flux surface averaged QN:

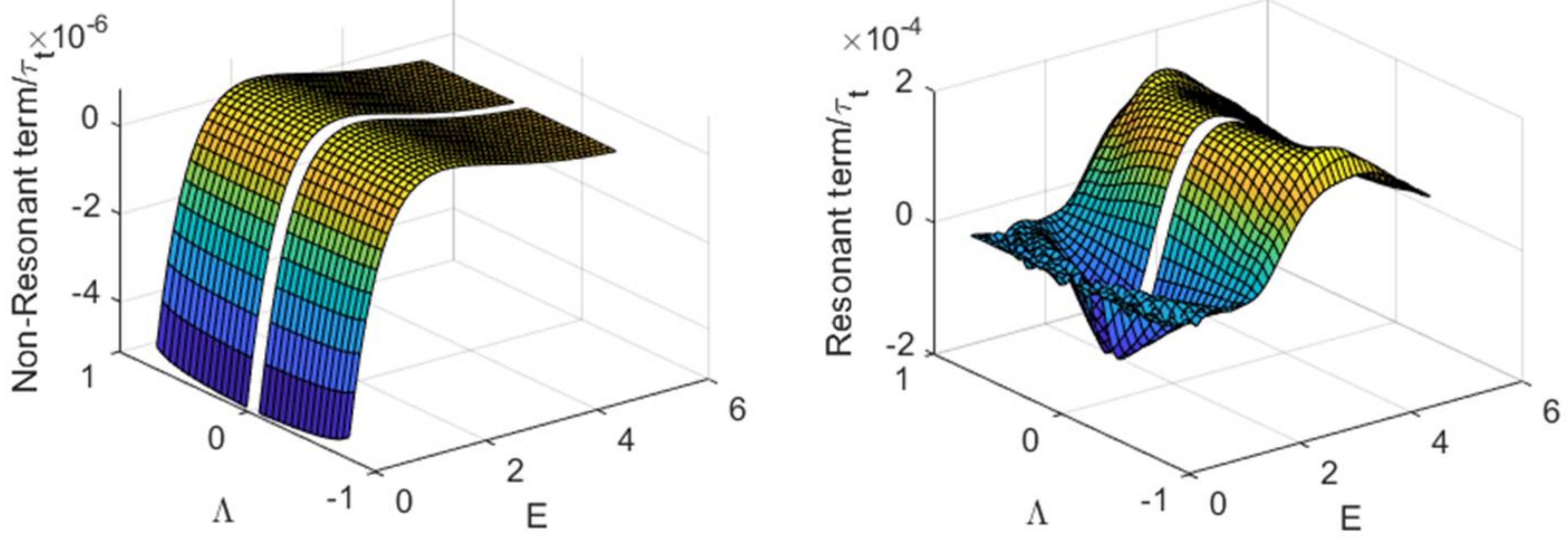
$$\sum_s \frac{V'_\psi}{4\pi^2}\frac{e^2}{m_s^2}\left\langle\left\langle \frac{\partial F_{z0}}{\partial\mathcal{E}}\delta\phi_z - e^{-iQ_z}\hat{I}_0\overline{e^{iQ_z}\hat{I}_0\frac{\partial F_{z0}}{\partial\mathcal{E}}\delta\phi_z}\right\rangle_v\right\rangle_\psi =$$

$$\sum_s\sum_\sigma\int d\mathcal{E}d\mu\tau_B e\frac{i}{\omega}\overline{\overline{e^{iQ_z}\hat{I}_0e^{iQ_z}NL}}$$

- F_{z0} is an arbitrary (renormalized) anisotropic distribution function;

PHASE SPACE FLUXES FROM DAEPS

- Phase space fluxes, e.g., induced by a TAE, can be calculated using a local code, i.e., DAEPS [6]
- Nonlinearity is considered by self consistent solution for the radial envelope (NLSE) [3]
- Phase space fluxes can be analyzed separating non resonant and resonant contributions



TAE induced diffusive flux on DTT (Divertor Tokamak Test)] respectively due to non-resonant and resonant particles calculated by DAEPS [6]

CONCLUSIONS

- we have introduced the concept of zonal state to describe the evolution of the plasma between neighboring nonlinear equilibria;
- governing equations for all the components of the ZS have been derived;
- the system is closed by the governing equations for em potentials.
- phase space fluxes have been calculated for realistic DTT plasmas

[1] L. Chen and F. Zonca, Reviews of Modern Physics 88.1 (2016), [2] Falessi M V and Zonca F 2019 Physics of Plasmas 26.2, [3] Zonca F, Chen L, Falessi M and Qiu Z 2021 Journal of Physics: Conference Series 1785 [4] F. Zonca et al. New Journal of Physics 17.1 (2015), [5] Falessi M V Chen L, Qiu Z and Zonca F 2021 to be submitted to New Journal of Physics, [6] Briguglio S et al. Physics of Plasmas 2.10, [6] Y. Li et al. Physics of Plasmas 27.6 (2020): 062505

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