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Fishbone instability and transport of energetic particles

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Summary

- **Energetic particles (EP)** known to impact MHD instabilities, potentially inducing EP transport, as discovered experimentally^[1,2]
- Extensive **theoretical linear works** done over the past decades^[3,4,5,6]
- **Non-linear hybrid codes**^[9,11,12,13,15], verified by comprehensive linear models and codes^[7,8,16], are needed to capture the physics of the fishbone induced EP transport
- **Full orbit nonlinear hybrid code**^[15] useful to investigate the physics of high energy alpha particles

Comprehensive linear model

The kinetic internal kink dispersion relation^[4,7,8,16]

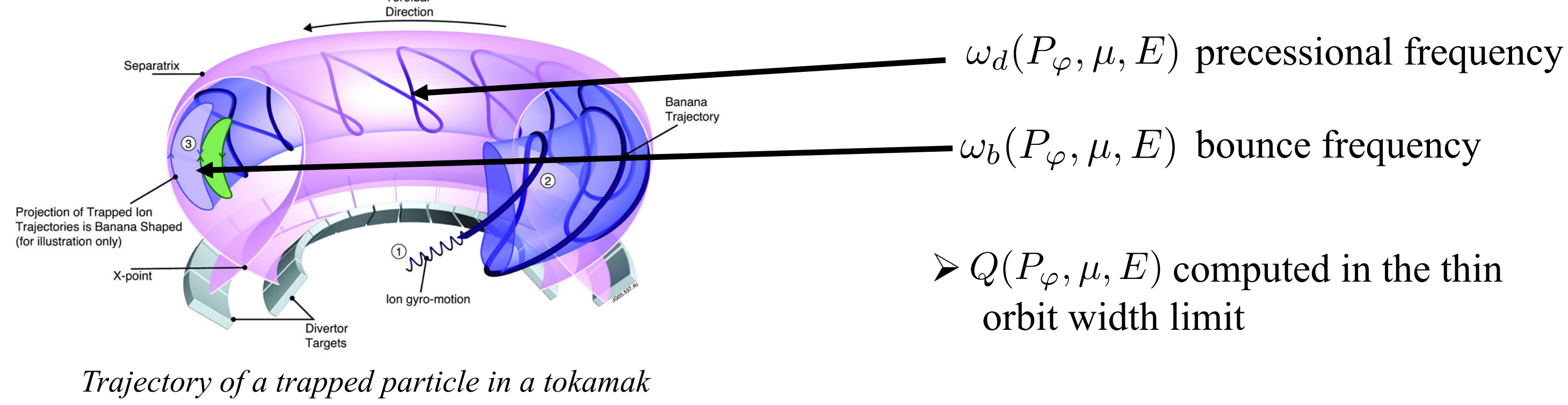
$$D(n_{h,0}, \Omega) = \delta I(\Omega) - i[\delta W_{MHD} + \delta W_K(n_{h,0}, \Omega)] = 0$$

$$\delta I(\Omega) \propto \Omega = \omega + i\gamma \in \mathbb{C}$$

δW_{MHD} computed by CHEASE/XTOR-2F^[14]

Complex resonant kinetic contribution, computed numerically^[4,7,8,16]

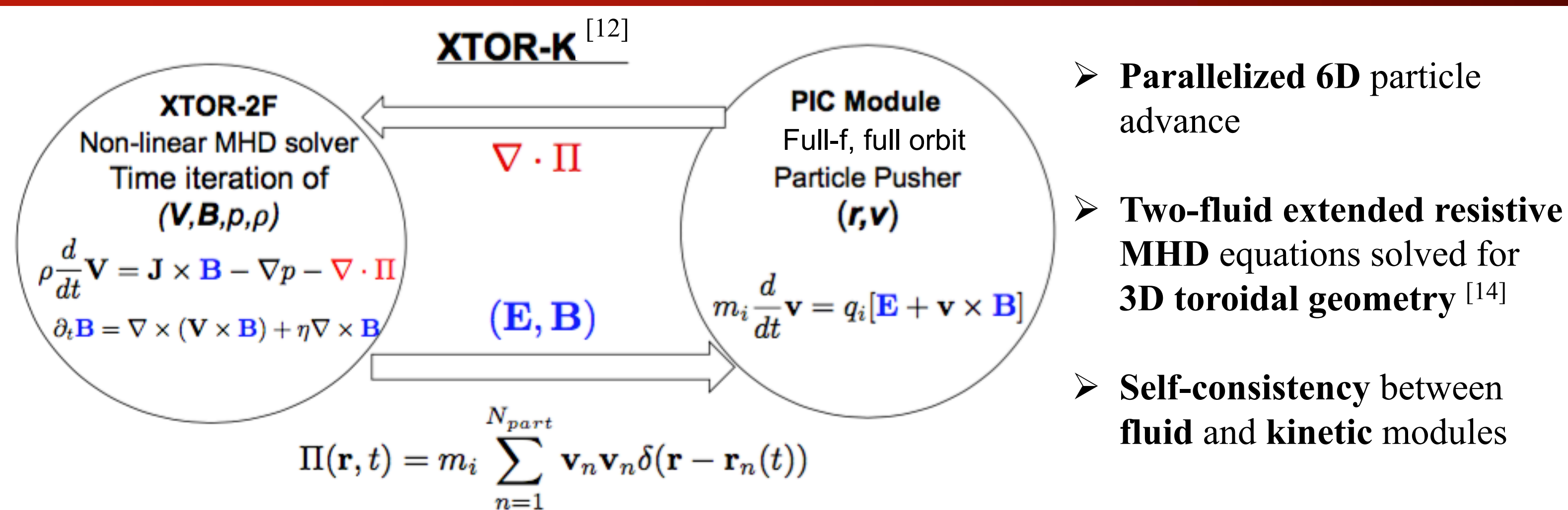
$$\delta W_K \propto \sum_{n_2} \int dP_\varphi d\mu \int_0^{E_\alpha} \frac{Q(P_\varphi, \mu, E)}{\Omega - (n_2 + q\delta_p)\omega_b - \omega_d} dE$$



Specificities of the linear model

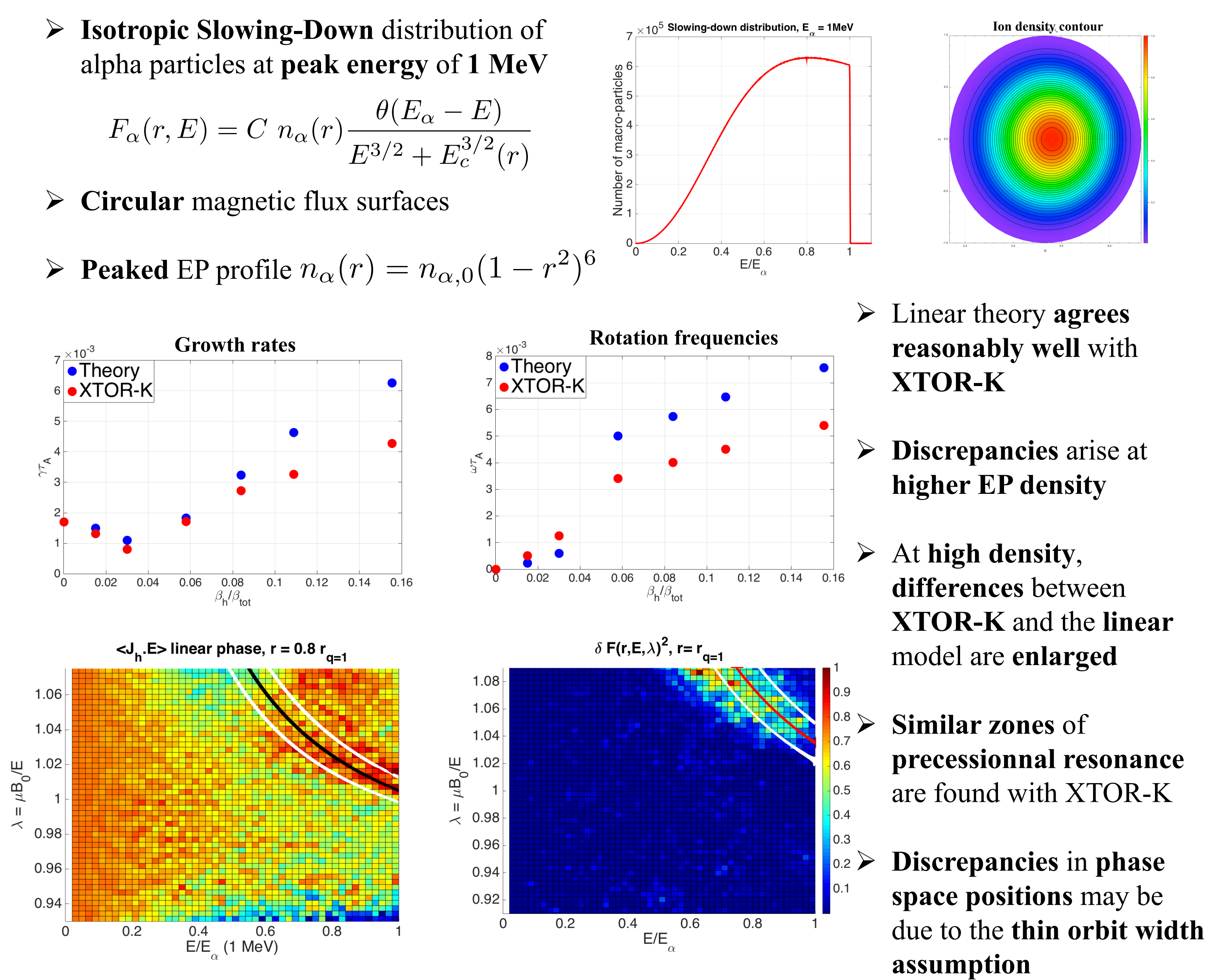
- Effects of passing particles taken into account
- Resonant integral solved analytically or numerically
- Fluid terms kept in the kinetic contribution
- Solves non-perturbatively the implicit dispersion relation

Description of the hybrid code XTOR-K

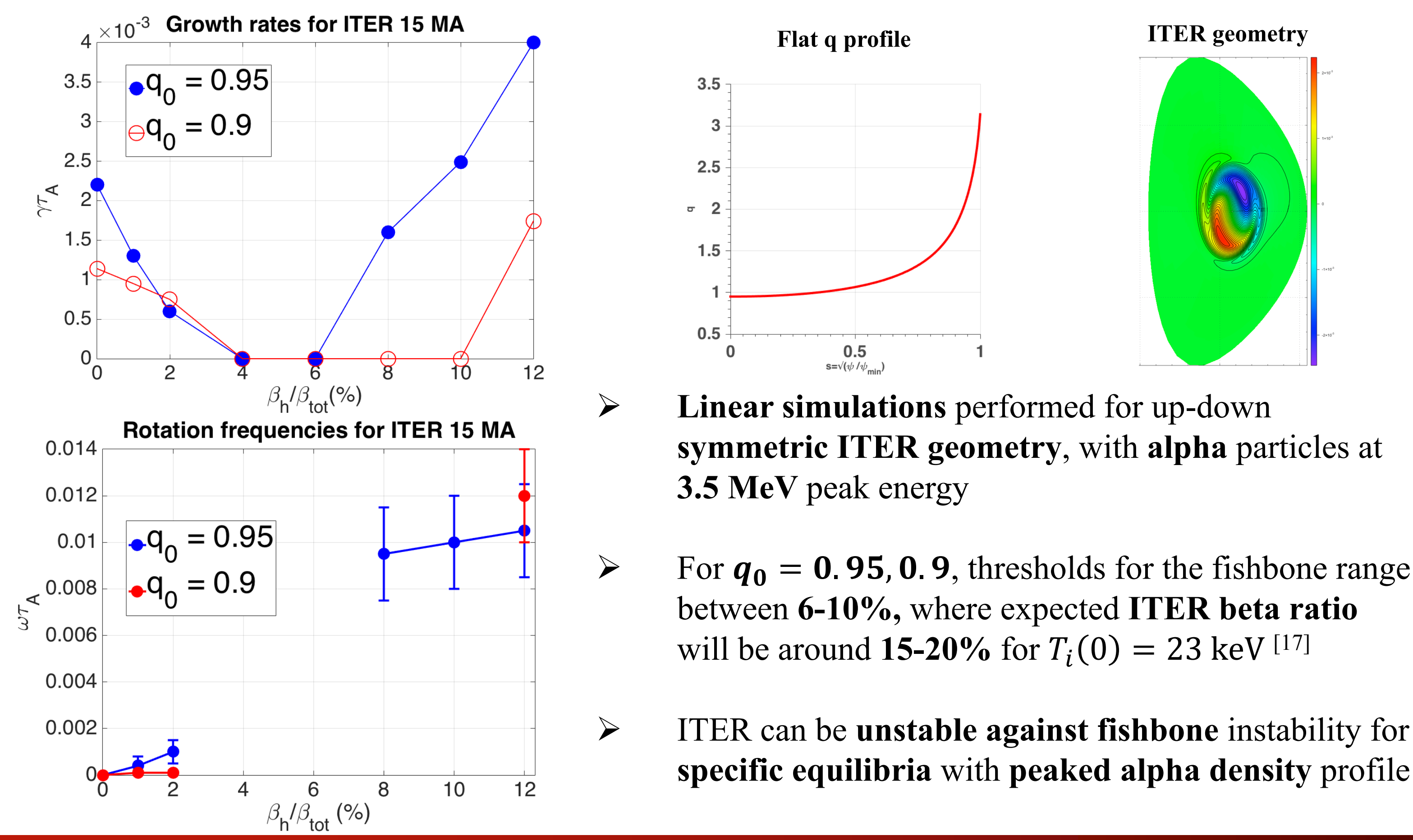


- Parallelized 6D particle advance
- Two-fluid extended resistive MHD equations solved for 3D toroidal geometry^[14]
- Self-consistency between fluid and kinetic modules

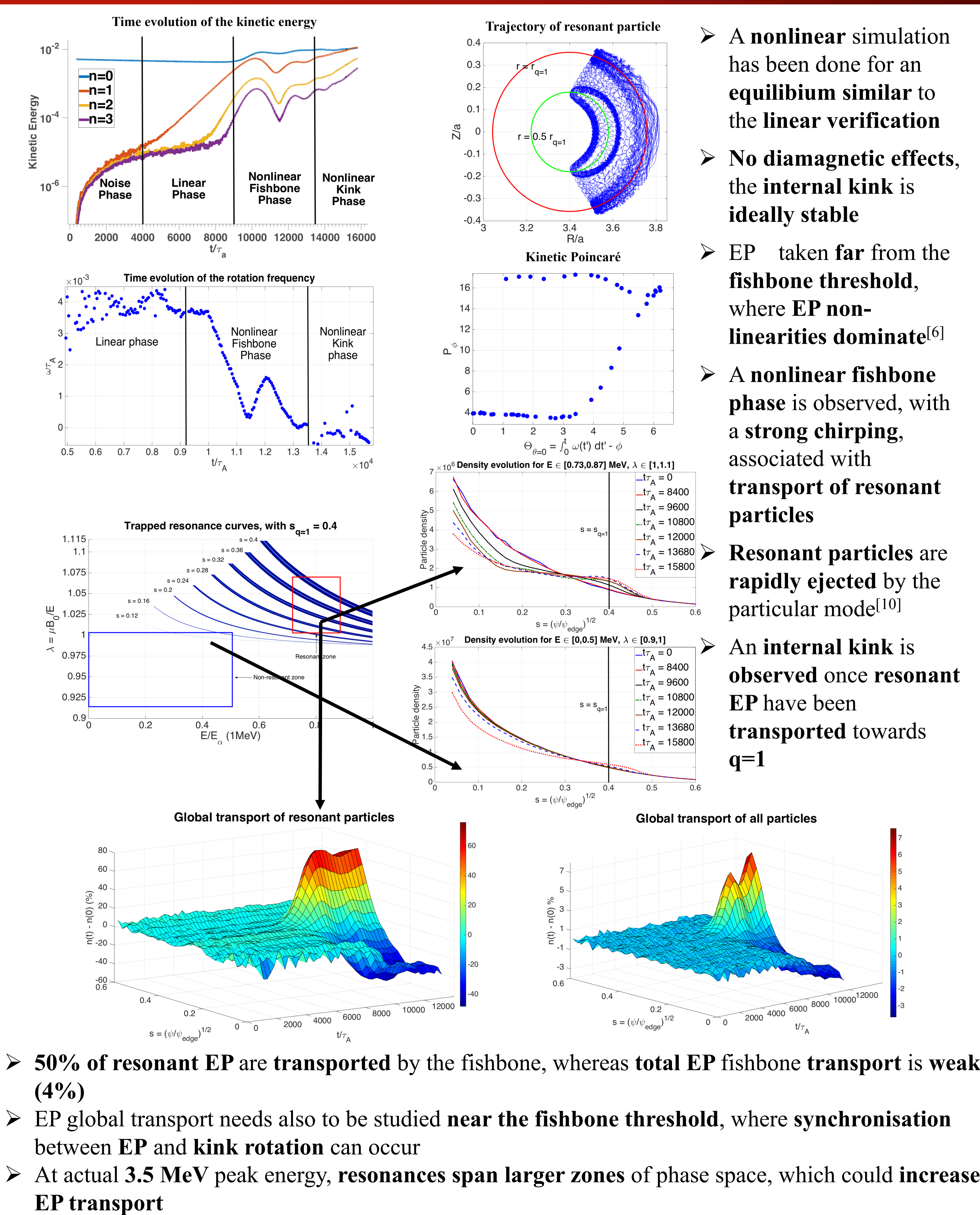
Linear verification of XTOR-K



Linear stability of the ITER 15 MA case



Fishbone nonlinear simulation



Conclusion

- Newly implemented nonlinear hybrid code XTOR-K verified linearly
- ITER 15 MA can be fishbone unstable for specific equilibria
- Global EP transport due to fishbone found weak far from fishbone threshold at 1 MeV
- More advanced kinetic Poincaré diagnostics needed to understand the nonlinear interplay between mode chirping and EP transport
- An other nonlinear simulation needed to generalize results near fishbone threshold for more ITER relevant equilibrium

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