Fishbone instability and transport of energetic particles

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Context

- **Energetic particles** (EP) known to impact **MHD instabilities**, potentially inducing **EP transport**, as discovered **experimentally**[1,2], which could reduce performances of burning plasmas
- Extensive **theorerical 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

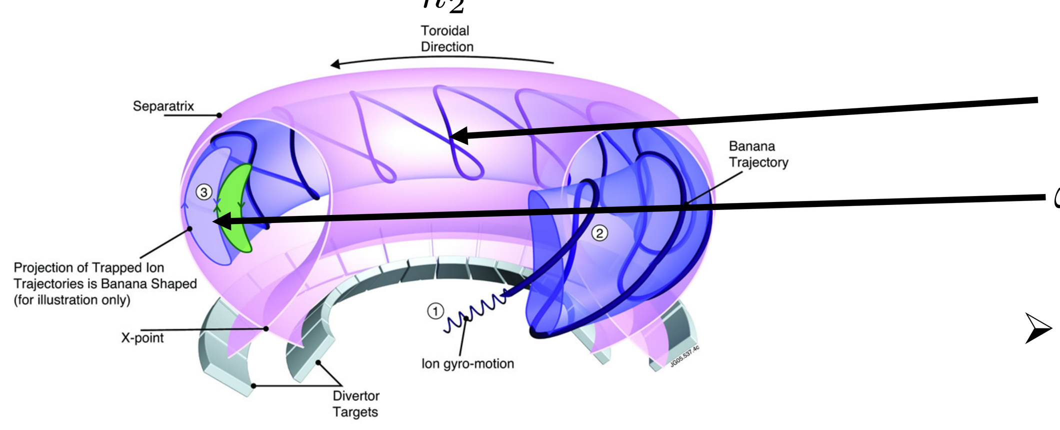
The kinetic internal kink dispersion relation[4,7,8,16]

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

$\delta I(\Omega) \propto \Omega = \omega + i\gamma \in \mathbb{C}$ $\qquad$ δW_{MHD} computed by CHEASE/XTOR-2F[14]

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

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



$\omega_d(P_\varphi,\mu,E)$ precessional frequency

$\omega_b(P_\varphi,\mu,E)$ bounce frequency

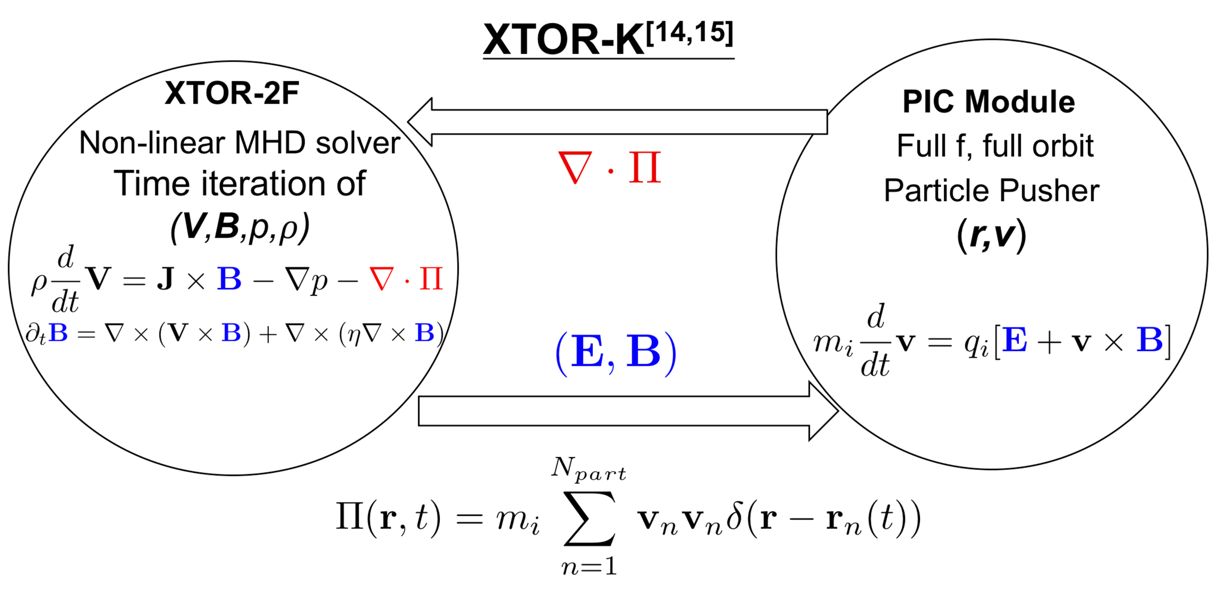
- $Q(P_\varphi,\mu,E)$ computed in the thin orbit width limit

Trajectory of a trapped particle in a tokamak

Specificities of the linear model

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

Hybrid Kinetic-MHD code XTOR-K



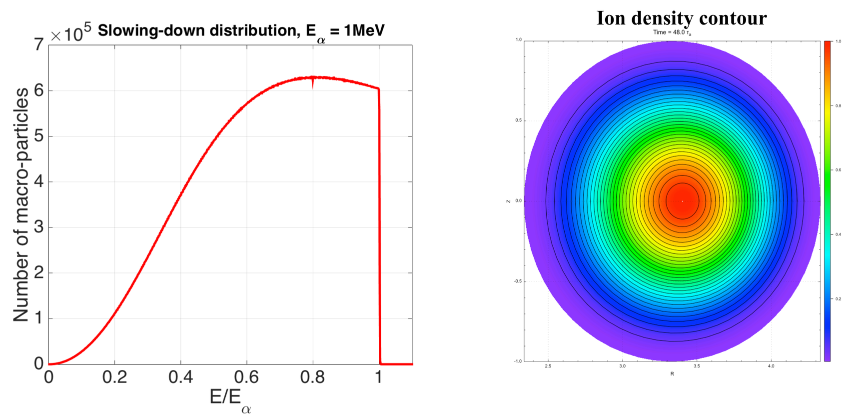
- **Parallelized 6D** particle advance
- **Two-fluid extended resistive MHD equations solved for 3D toroidal geometry** [14]
- **Self-consistency** between **fluid and kinetic** modules

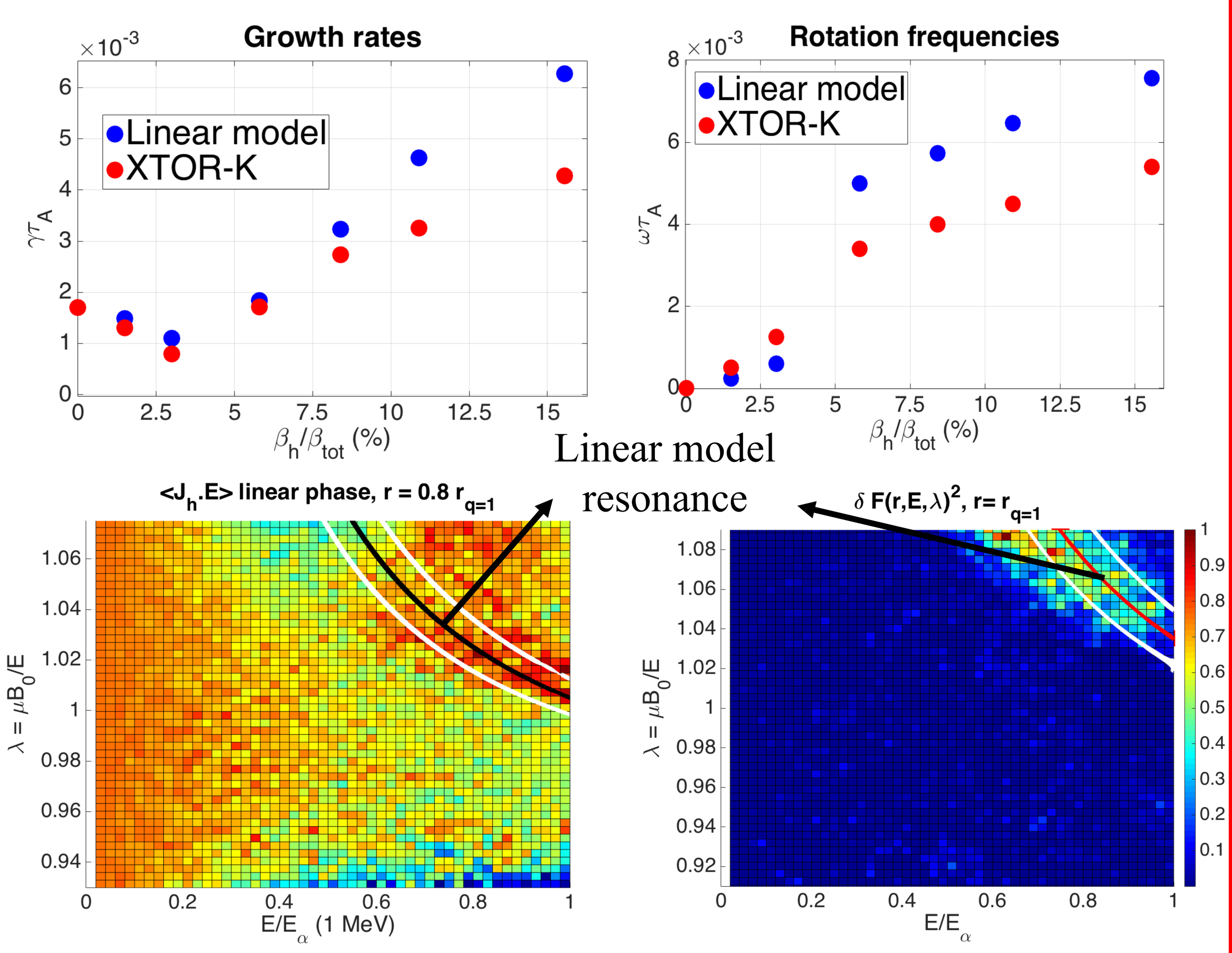
Linear model VS XTOR-K : Good agreement

- **Isotropic Slowing-Down** distribution of alpha-like particles at **peak energy of 1 MeV**

$$F_\alpha(r,E) = C\, n_\alpha(r)\frac{\theta(E_\alpha - E)}{E^{3/2} + E_c^{3/2}(r)}$$

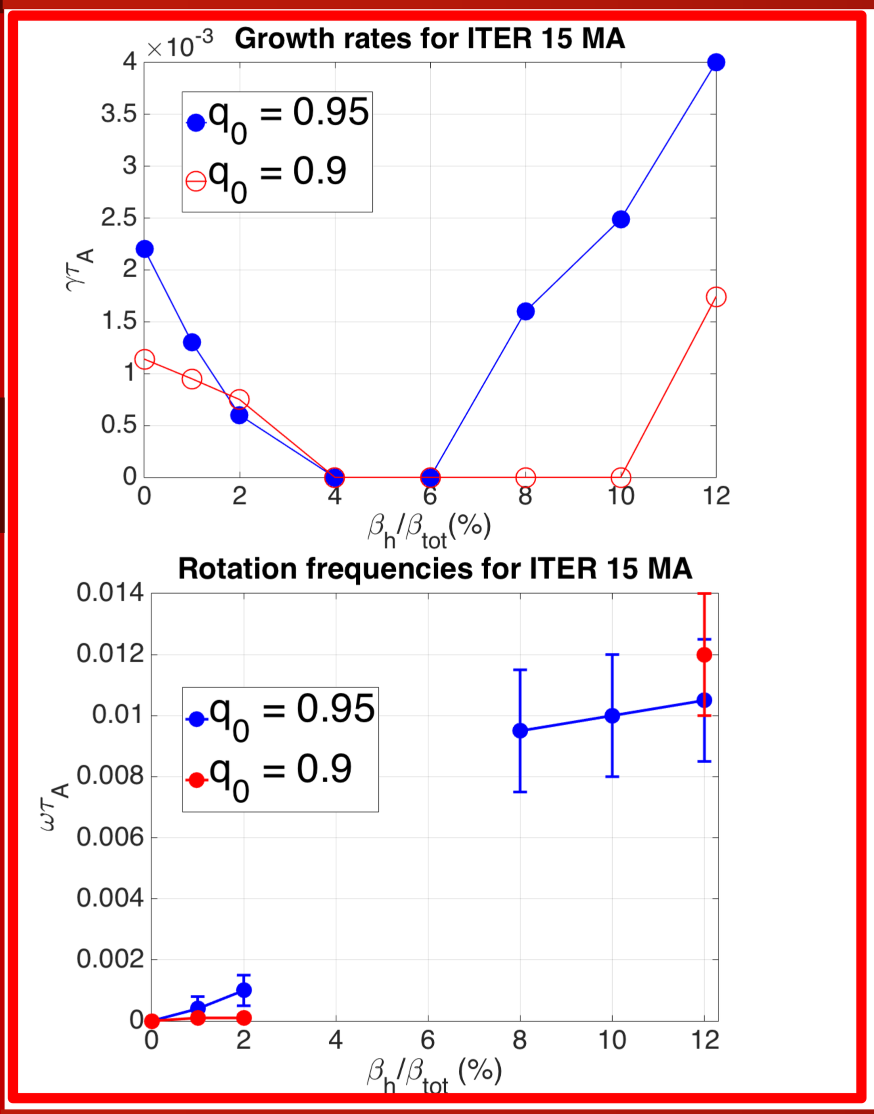
- **Circular** magnetic flux surfaces
- **Peaked** EP profile $n_\alpha(r) = n_{\alpha,0}(1-r^2)^6$

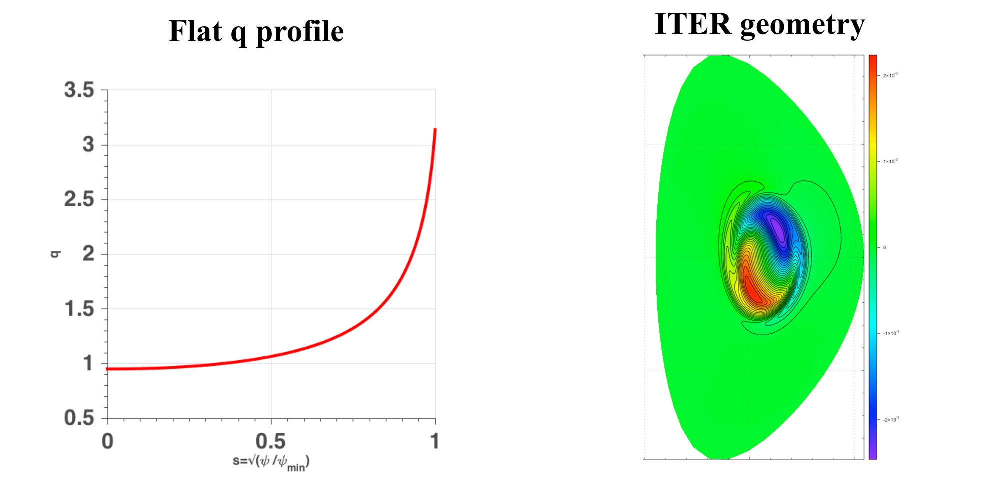




- **Linear theory agrees well with XTOR-K**
- **Discrepancies** arise at **higher EP density**
- At **high density, differences** between **XTOR-K** and the **linear** model are **enlarged**
- **Similar zones of precessionnal resonance** are found with XTOR-K
- **Discrepancies in phase space positions** may be due to the **thin orbit width assumption**

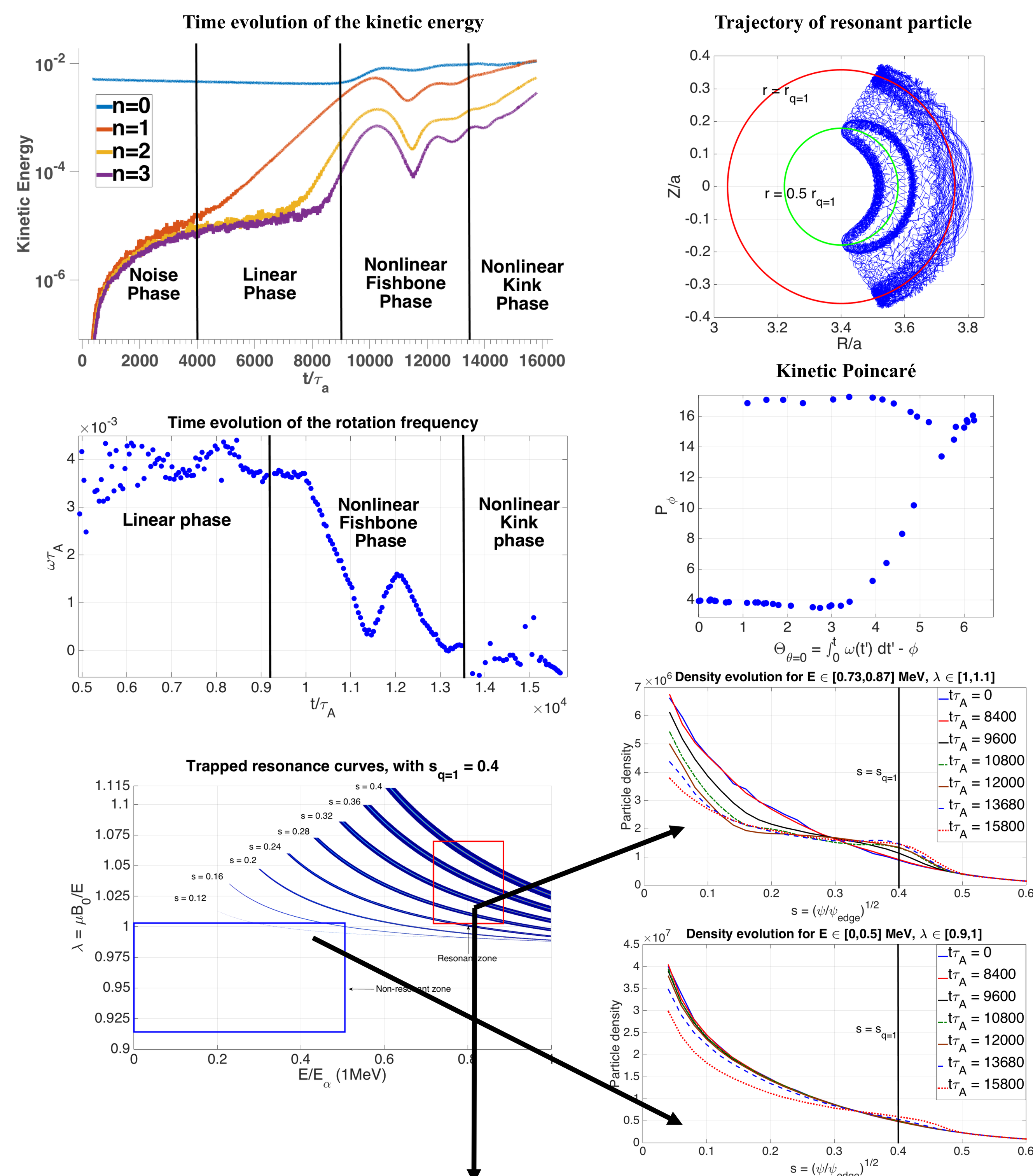
ITER 15 MA scenario may be fishbone-unstable



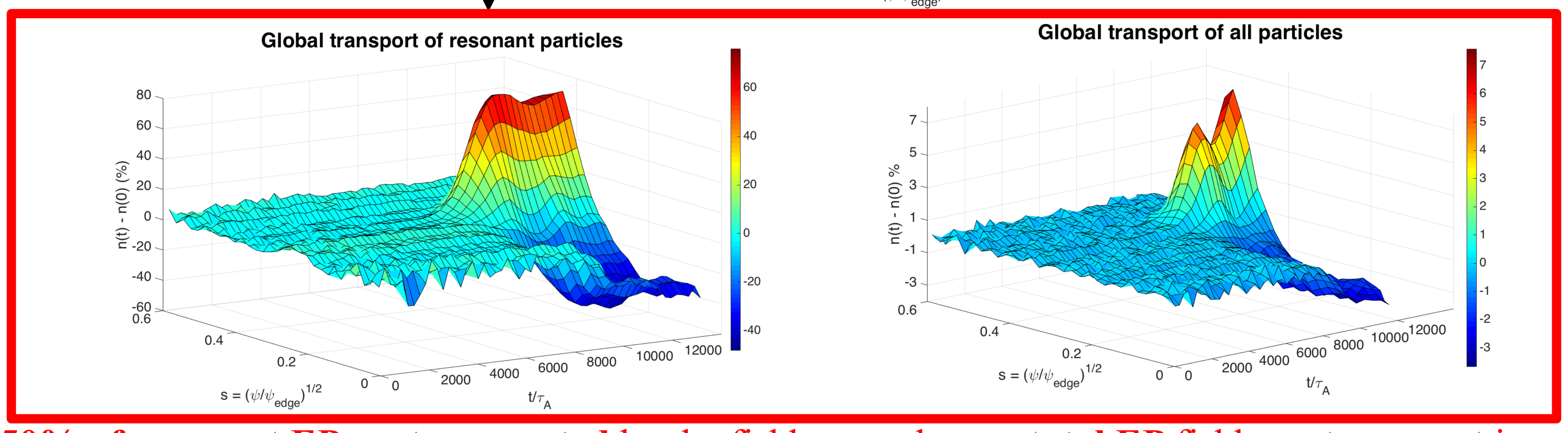


- **Linear simulations** performed for up-down **symmetric ITER geometry**, with **alpha** particles at **3.5 MeV** peak energy
- For $q_0 = 0.95, 0.9$, thresholds for the fishbone range between **6-10%,** whereas expected **ITER beta ratio** will be around **15-20%** for $T_i(0) = 23$ keV [17]
- ITER can be **unstable against fishbone** instability for **specific equilibria** with **peaked alpha density** profile

Nonlinear : Fishbone-induced EP transport



- A **nonlinear** simulation has been done for an **equilibium similar** to the **linear verification**
- **No diamagnetic effects,** the **internal kink** is **ideally stable**
- EP density taken **far** from the **fishbone threshold**, where **EP non-linearities dominate**[6]
- **A nonlinear fishbone phase** is observed, with a **strong chirping,** associated with **transport of resonant particles**
- **Resonant particles** are **rapidly exiting** the model[10]
- After the **fishbone saturation**, the **growth** of an **internal kink** is observed



- **50% of resonant EP** are **transported** by the fishbone, whereas **total EP** fishbone **transport** is **weak (4%)**
- EP global transport needs also to be studied **near the fishbone threshold**, where **synchronisation** between **EP and kink rotation** can occur
- At actual **3.5 MeV** peak energy, **resonances span larger zones** of phase space, which could **increase EP transport**

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**
- **Another nonlinear simulation** needed to **generalize** results **near fishbone threshold** for more **ITER relevant** equilibrium

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