DE LA RECHERCHE À L'INDUSTRIE

CEA/CNRS contribution to TSVV10 project

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XTOR-K[1,2]

[1] H. Lütjens et al, JCP 2012
[2] D. Leblond, PhD thesis 2013

XTOR-2F

Non-linear MHD solver
Time iteration of
(**V**,**B**,p,ρ)

$$\rho \frac{d}{dt}\mathbf{V} = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi$$

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \eta \nabla \times \mathbf{B}$$

$$\nabla \cdot \Pi$$

$$(\mathbf{E}, \mathbf{B})$$

PIC Module

Particle Pusher
(**r**,**v**)

$$m_i \frac{d}{dt}\mathbf{v} = q_i[\mathbf{E} + \mathbf{v} \times \mathbf{B}]$$

$$\Pi(\mathbf{r}, t) = m_i \sum_{n=1}^{N_{part}} \mathbf{v}_n \mathbf{v}_n \delta(\mathbf{r} - \mathbf{r}_n(t))$$

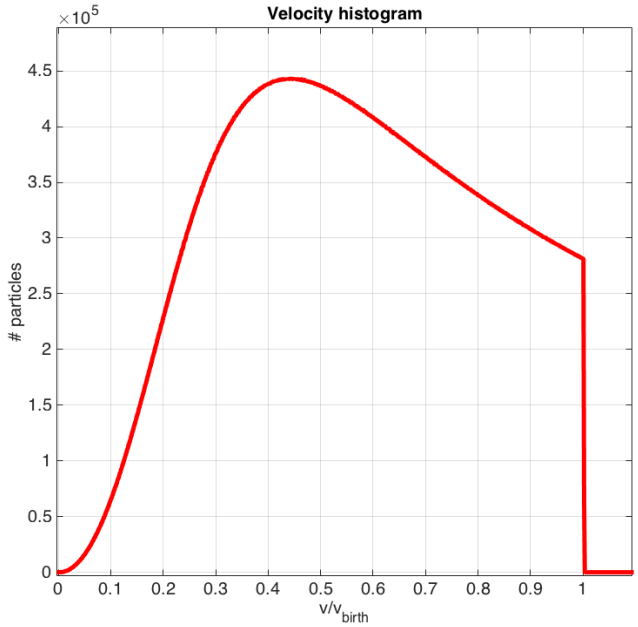
Main results from G. Brochard's PhD thesis (10/2016-09/2019)

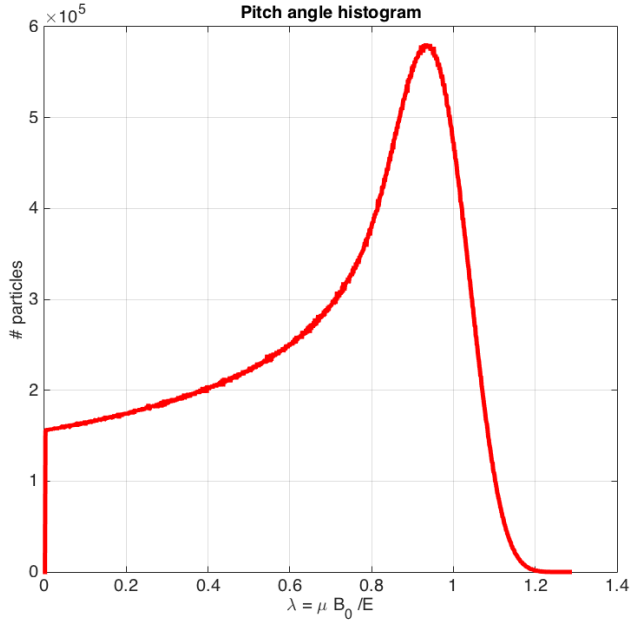
- Linear semi-analytical developed for the verification of XTOR-K [Brochard, JCPS 2018]
- Implementation of slowing-down distributions [Brochard, NF 2020a]
- Linear [Brochard, NF 2020a] and non-linear [Brochard, NF 2020b] study of alpha-driven fishbones in ITER

Arbitrary energetic particle distributions implemented in XTOR-K

- **Isotropic slowing-down:** $F_{eq}(r,v) \equiv n_f(r) C \frac{H(v_b - v)}{v^3 + v_c^3}$

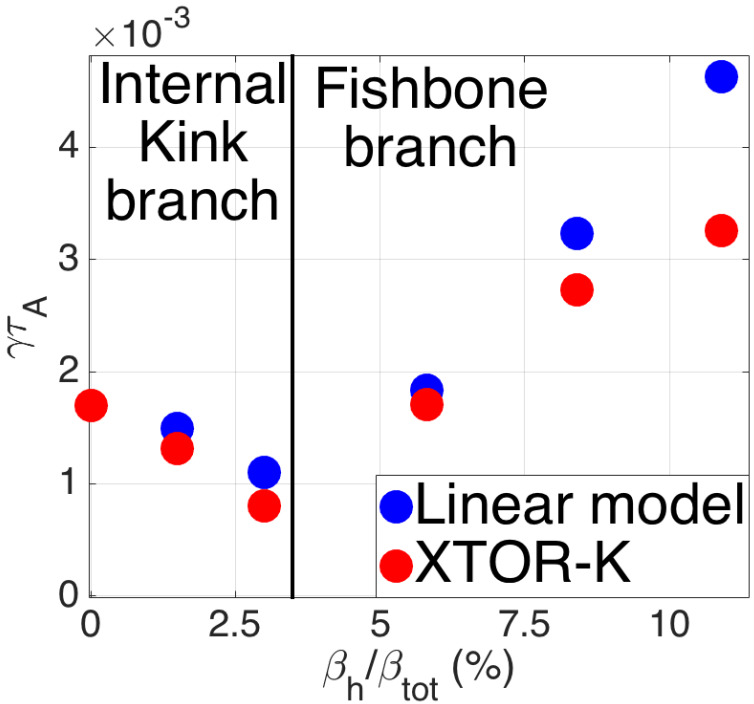
- **Typical resulting histograms in XTOR-K** (alphas at 3.5MeV, $T_e(0)$=20keV):

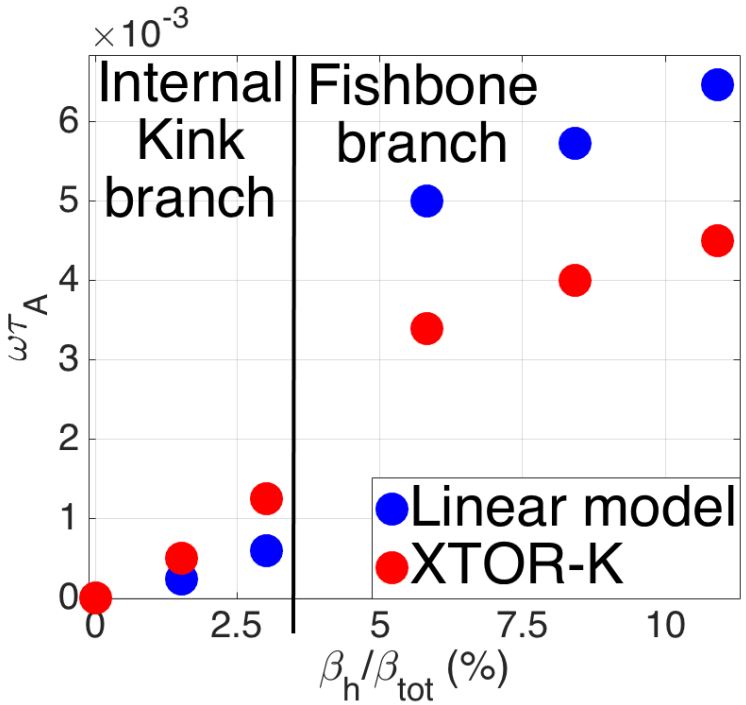




- Implementation of same slowing-down distributions in linear model and in XTOR-K
- Can be generalized to other distributions (anisotropic…)
- For XTOR-K, development of computational workflow (including equilibrium solver CHEASE) to initialize fluid profiles, geometry, particle distributions…

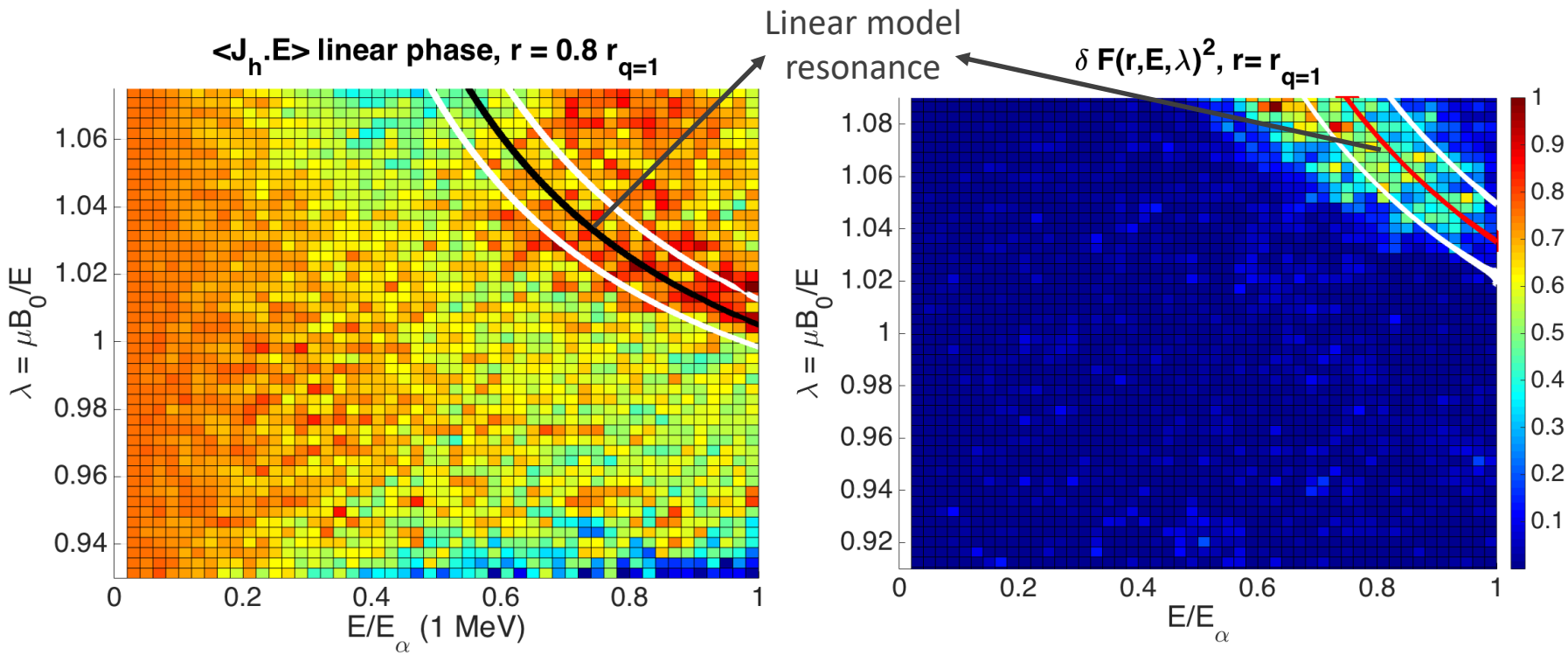
Linear verification of XTOR-K





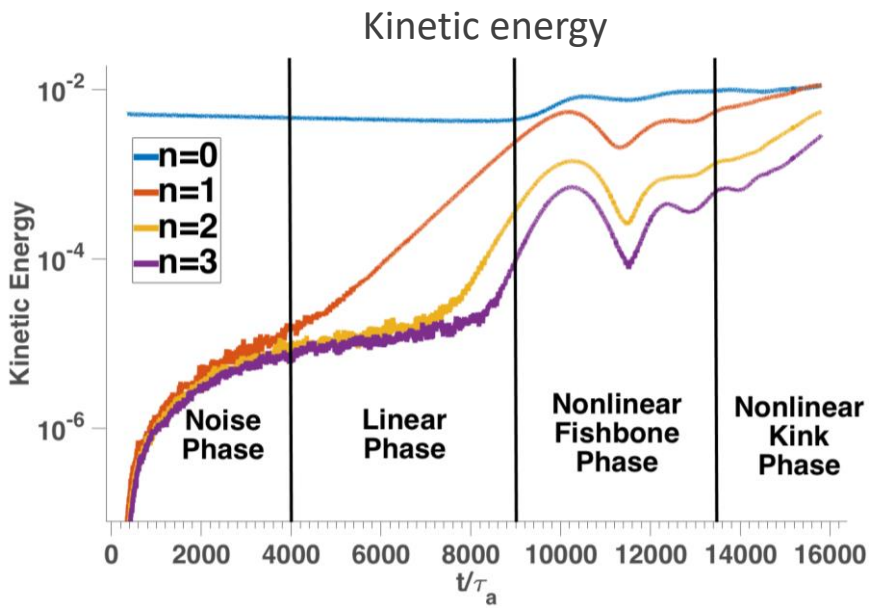
- Linear theory agrees reasonably well with XTOR-K
- Discrepancies arise at larger EP densities
- At high densities / particle energies, assumptions underlying the linear model increasingly questionable (influence of wide / non-standard orbits, impact of energetic ion pressure on background equilibrium…)

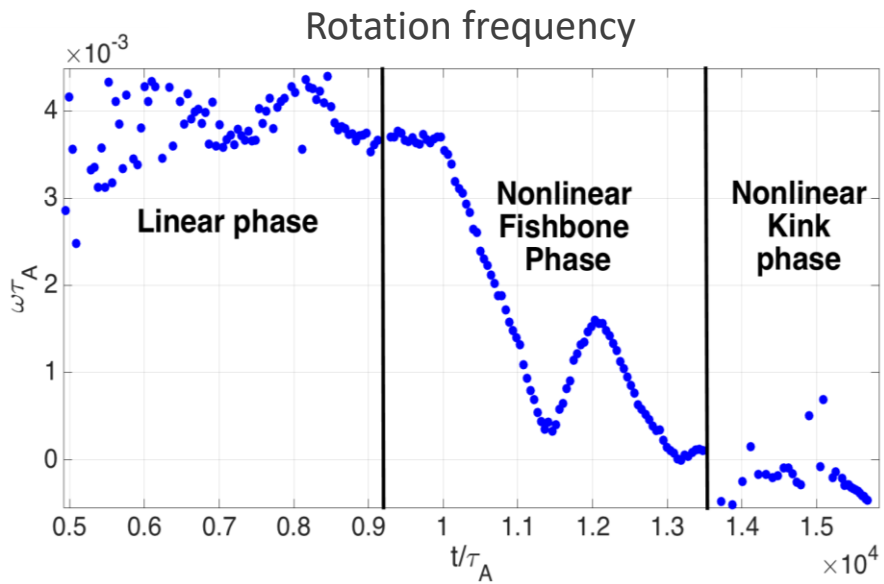
Linear verification of XTOR-K (cont'd)



- Zones of precessional resonance in nonlinear XTOR-K simulations fairly well described by linear model
- Energy exchange maps noisy because the end of the linear phase is only a few rotation periods (averaging)
- Moderate discrepancies in phase space positions attributed to the zero-orbit width assumption

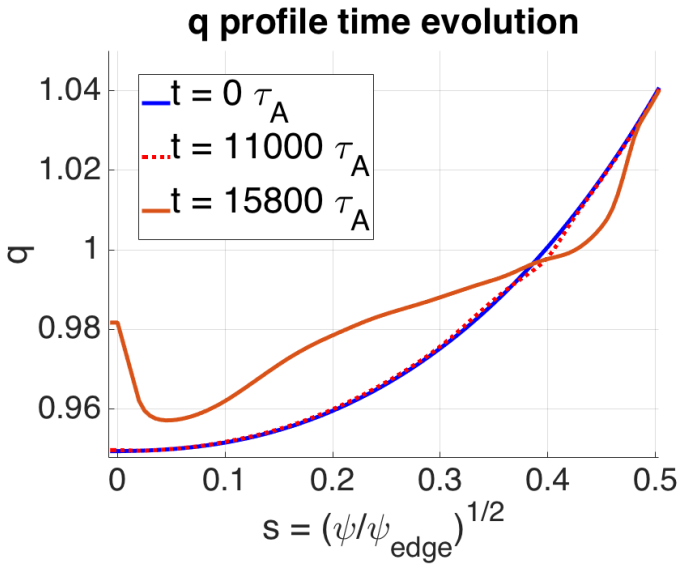
Nonlinear simulation of the fishbone instability

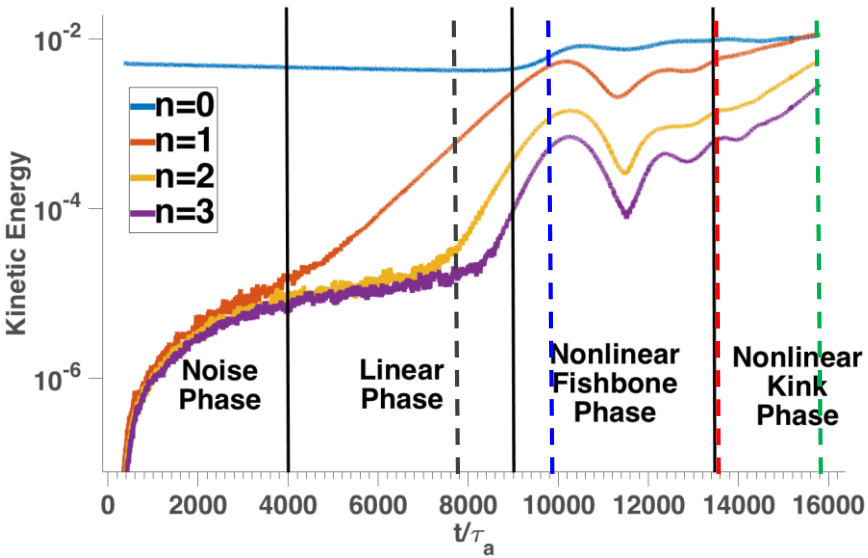




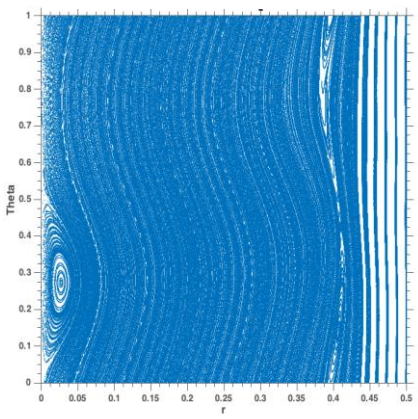
- Above : first non-linear simulations performed for a circular equilibrium, with EP birth energy at 1 MeV – Simulations with ITER equilibrium + 3.5MeV alphas presented in [Brochard, NF 2020b]
- Fishbone oscillations observed before reconnection due to the kink instability
- Chirping associated with the fishbone oscillations, as well as mode saturation
- Instability rotation frequency goes to zero in the kink phase

Fishbone oscillations



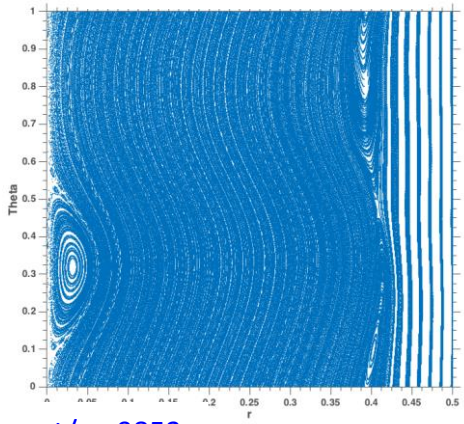


Start of fishbone phase



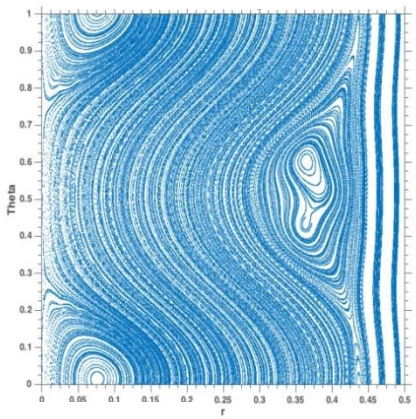
t/τ_a=7757

Saturated fishbone phase



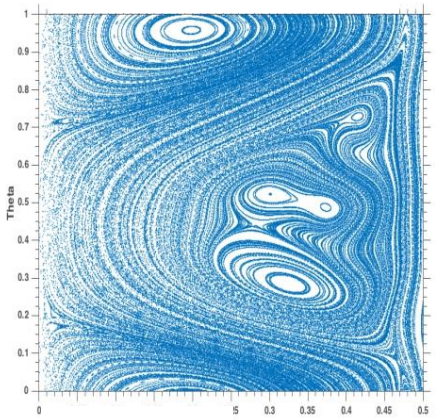
t/τ_a=9853

End of fishbone phase



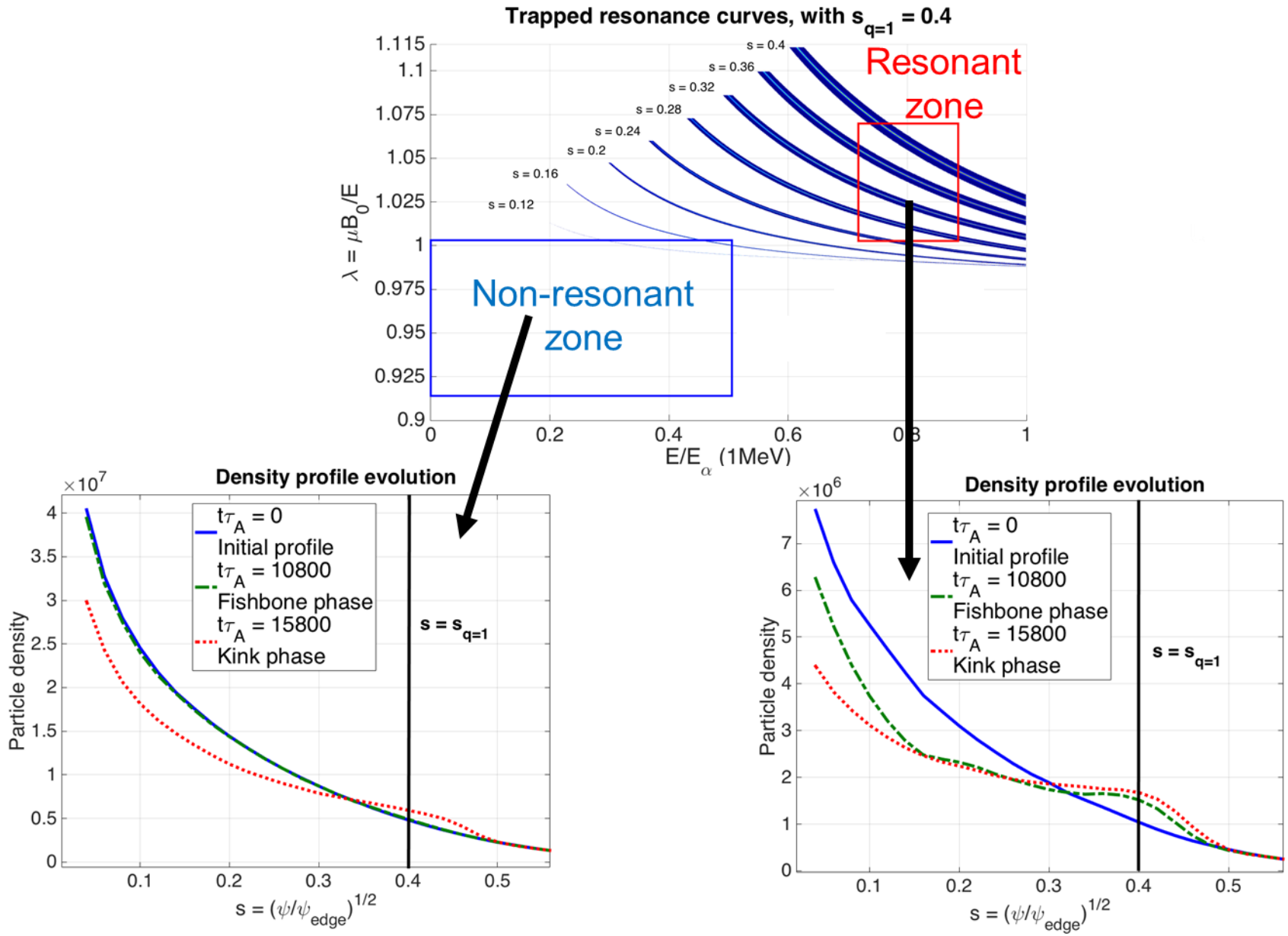
t/τ_a=13614

Kink phase



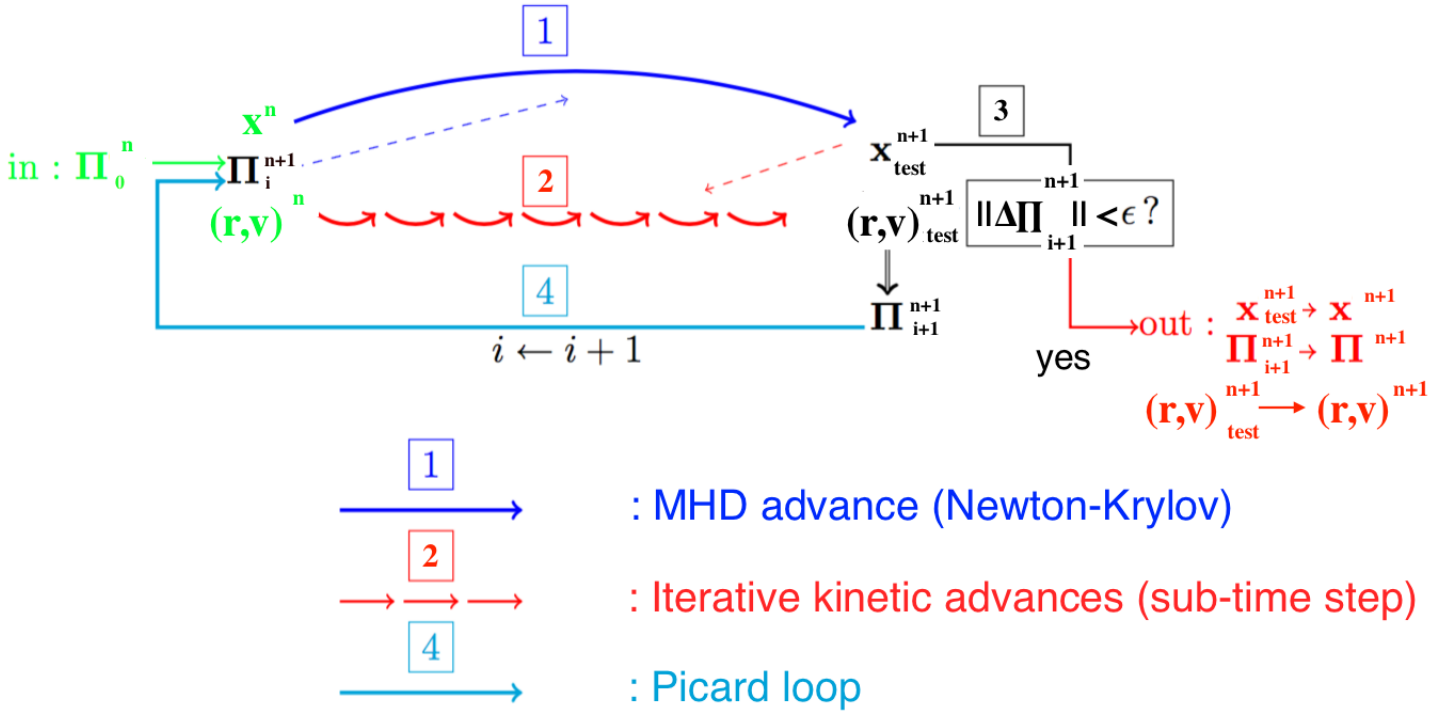
t/τ_a=15801

Distribution function time evolution



XTOR-K hybrid time stepping (1/2)

- Fluid integrator: Implicit pre-conditioned Newton-Krylov
- Particle integrator: Boris-Buneman
- Both integrators converge together inside a Picard loop



- Particle time step fixed during entire simulation (~20 per giration)
- Fluid time step variable to control NK iterations

XTOR-K hybrid time stepping (2/2)

Consequences:

- Numerical cost of particle part constant: does not depend on linear or nonlinear phase of simulation. 2-3 particle iterations per hybrid time step

- Fluid time step decreases strongly during kink saturation phase. Dimensions overall numerical cost in NL phase.
  Reason: NK iterates like hell. Min(dt fluid) = dt particle at moment

How are we going to solve this?

- Parallelization of the fluid part adding radial domain decomposition: A first version of this solver was developed for XTOR-2F, using a SPIKE algorithm. An improved version was implemented into XTOR-K, in test phase

- Improve the fluid/kinetic interface. More flexibility in handling the different time steps / ion species / particle integrators

- Work on the linear model in the physical pre-conditioner.

CEA/CNRS contributions to E-TASC TSVV10 project

4. MHD stability in presence of a large fusion alpha population

- **Dec 2023:**
  (S) Linear kink stability in the presence of fast particles and Alfvén Eigenmodes.
  (M) Linear and nonlinear hybrid-MHD simulations (XTOR) of internal kink modes in the range of a single sawtooth period in the presence of Alfvén Eigenmodes and fast particles
- **Dec 2025:**
  (S) Nonlinear kink stability in the presence of fast particles and Alfvén Eigenmodes.
  (M) Nonlinear hybrid-MHD simulations of sawtooth oscillations with the XTOR code family including fast ions and using the pressure tensor provided by the reduced models of the fast-particle evolution in the presence of Alfvénic modes

5. Burn control and energy deposition optimization strategies

- **Dec 2025:**
  (S) ITER burning-plasma ETS simulations using reduced fast-ion models.
  (M) Perform extensive burning-plasma scenario studies using ETS and the most efficient fast-ion transport models coupled through an IMAS interface.

6. Reduced models for AE/EPM stability and nonlinear dynamics

- **Dec 2025:**
  (S) Implementation of phase-space resolved fluxes into the transport solver (ETS), as given by the kick model or more advanced nonlinear computations or models.
  (M) Compare the performance (accuracy vs. speed) of time dependent transport simulations with phase-space resolved EP transport models to the CG model.

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