



Status of XTOR-K

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Outline:

- Physical model
- Method of solution
- Links with ACH supports
- Example 1: 2-fluid sawtooth oscillations
- Example 2: Hybrid 2-fluid/kinetic internal kink
- Example 3: ITPA $n=6$ TAE
- Projects

Physical model (1/2):

Fluid equation of motion: $\mathbf{v} = \mathbf{v}_{E \times B} + u_{\parallel}^i \hat{\mathbf{b}}$

$$\rho_i^m \partial_t \mathbf{v} + \rho_i^m (\mathbf{v} \cdot \nabla) \mathbf{v} + \rho_i^m (\mathbf{v}_i^* \cdot \nabla) \mathbf{v}_{\perp} + \partial_t \left(\sum_k \mathbf{J}_k^m \right) - \mathbf{J} \times \mathbf{B} + \nabla p_i + \nabla p_e + \sum_k \nabla \cdot \mathbf{P}_k - \rho_i^m \nabla \nu \nabla (\mathbf{v} + \mathbf{v}_i^*) = 0$$

Parallel bulk ion velocity:

$$\partial_t u_{\parallel}^i + (\mathbf{v} + \mathbf{v}_i^*) \cdot \nabla u_{\parallel}^i - [\nabla \nu \nabla (\mathbf{v} + \mathbf{v}_i^*)]_{\parallel} + \left[\frac{\nabla p_i}{m_i n_i} + \frac{Z_i \nabla p_e}{m_i n_e} \right]_{\parallel} - (\mathbf{v} + \mathbf{v}_i^*) \cdot \partial_t \hat{\mathbf{b}} = 0$$

Faraday:

$$\partial_t \mathbf{B} - \nabla \times ((\mathbf{v} + \mathbf{v}_e^*) \times \mathbf{B}) + \nabla \times \eta (\mathbf{J} - \mathbf{J}_0) = 0$$

Particle motion:

$$m_p \frac{d\mathbf{v}_p}{dt} = q_p (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\mathbf{v}_s^* = \frac{\mathbf{B} \times \nabla p_s}{q_s n_s B^2}$$

ρ_k = particle density

\mathbf{J}_k^q = particle current density

$$\mathbf{J}_k^m = m_k / q_k \mathbf{J}_k^q$$

\mathbf{P}_k = particle pressure tensor

Physical model (2/2):

Bulk ion density:

$$\partial_t n_i + \nabla \cdot (n_i \mathbf{v}) + \frac{1}{q_i} \nabla p_i \cdot \nabla \times \frac{\mathbf{B}}{B^2} - \nabla \cdot D_{\perp} \nabla n_i - S = 0$$

Ion and electron temperatures/pressures (without thermal transport terms)

$$\partial_t T_s = (\Gamma - 1) \frac{T_s}{q_s} \left(\frac{5}{2} \nabla T_s + \frac{\nabla p_s}{n_s} \right) \cdot \nabla \times \frac{\mathbf{B}}{B^2} - (\mathbf{v}_{\perp} + \mathbf{u}_{\parallel}^s) \cdot \nabla T_s - (\Gamma - 1) T_s \nabla \cdot (\mathbf{v}_{\perp} + \mathbf{u}_{\parallel}^s) \text{ for } s=i,e$$

$$\partial_t p_s = -\Gamma \frac{\nabla (T_s p_s)}{q_s} \cdot \nabla \times \frac{\mathbf{B}}{B^2} - (\mathbf{v}_{\perp} + \mathbf{u}_{\parallel}^s) \cdot \nabla p_s - \Gamma p_s \nabla \cdot (\mathbf{v}_{\perp} + \mathbf{u}_{\parallel}^s) \text{ for } s=i,e$$

Quasi-neutrality:

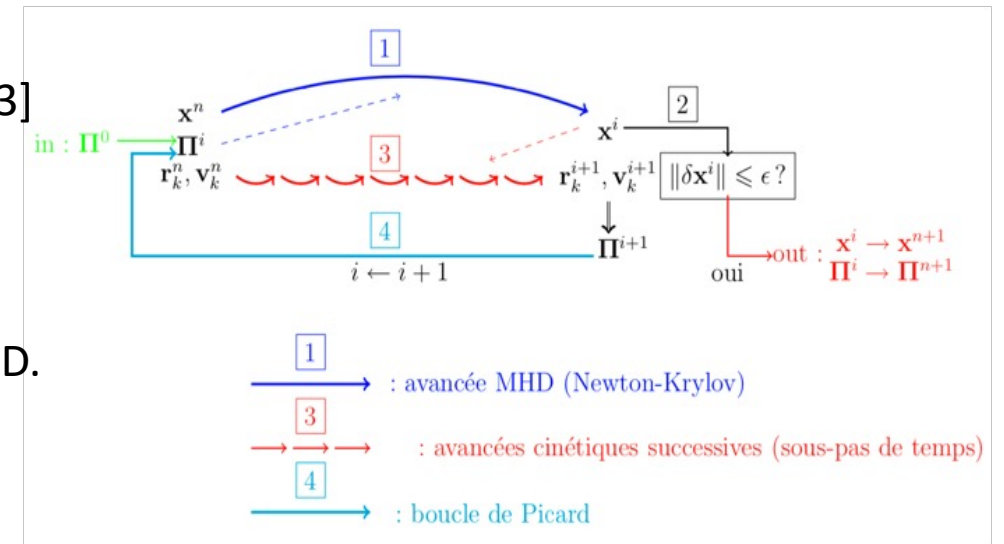
$$n_e = Z_i n_i + \sum_k Z_k n_k$$

Parallel electron velocity:

$$u_{\parallel,e} = v_{\parallel,e} = \frac{Z_i e n_i u_{i,\parallel} + \mathbf{J}_{kin,\parallel}^q - \mathbf{J}_{\parallel}}{e n_e}$$

Method of solution:

- $M^{-1} F(\mathbf{v}, \mathbf{B}, u_i^{\parallel}, n_i, T_i, T_e, \rho_k, \mathbf{J}_k, \mathbf{P}_k, \mathbf{x}, t) = 0$
 $M =$ physical pre-conditionner ($\eta\chi$ -MHD)
- Embedded Picard + matrix-free Newton Krylov iterative solver [1,3]
- M is inverted using parallel SPIKE LU [2]
- Boris Buneman pusher for particles
- Domain decompositions: Fluid: radial ; Particles cloning or (R,Z) DD.
- Solvers: PETSc SNES or nitsol
- PETSc allows easy change of M if available. Intended for DD.



[1]Lütjens et al, JCP **229** (2010) p.8130

[2]Marx et al, CPC 212 (2017) p.90

[3]<https://pastel.hal.science/file/index/docid/618453/filename/these.pdf>

LINKS with ACH supports

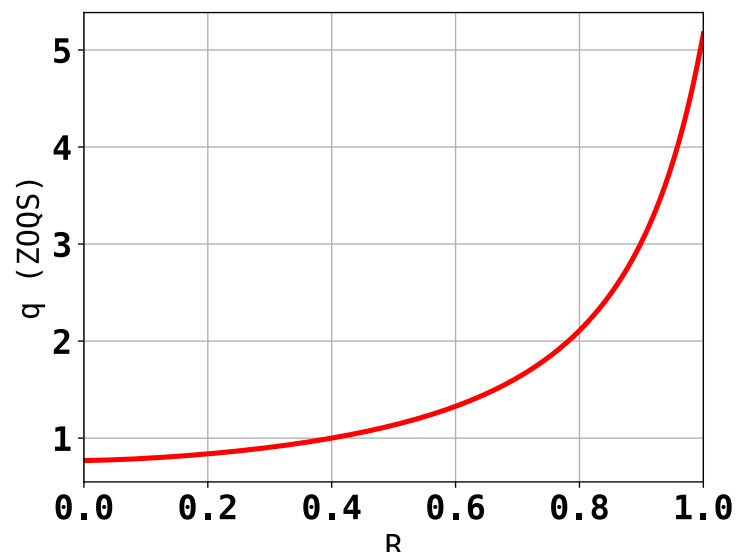
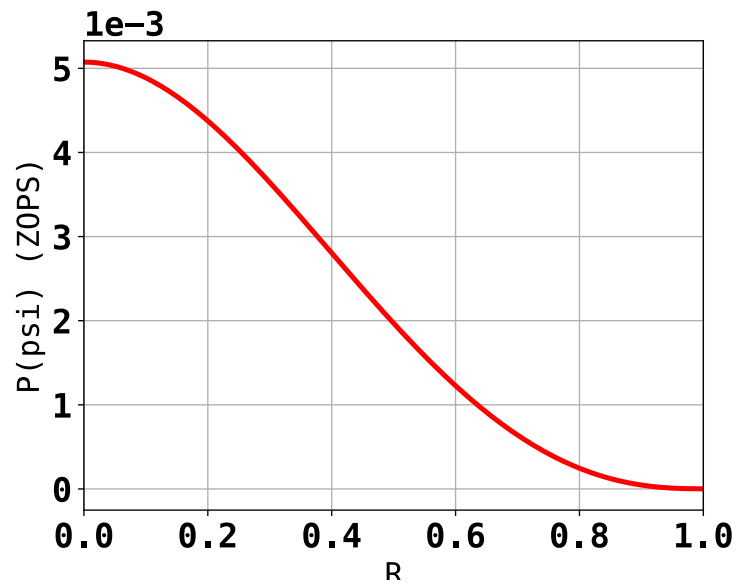
Migration towards GPU's: Support by BSC Barcelona (Eduardo Cabrera Flores Augusto Maidana):

- IDRIS Hackathon 2025: Particule pusher moved successfully towards MPI+GPU
- Move fluid/kinetic interface towards GPU: started
- Fluid part: TBD

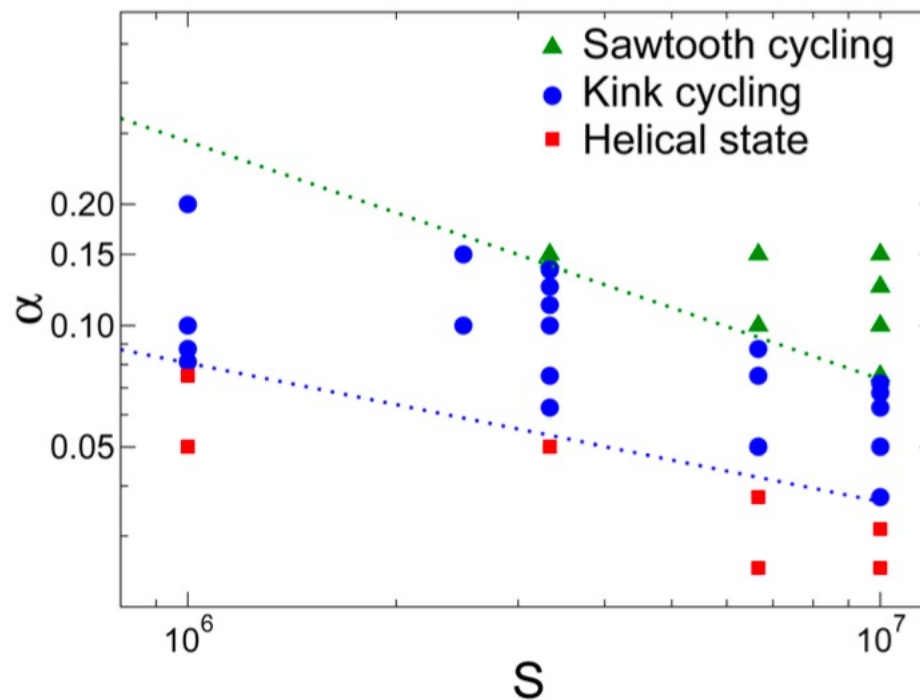
Code IMASification: Support by Michal Czarski (IPPLM) Frederic Imbeaux (Cadarache) and Rui Coelho (IST)

- Pressure pre-processing + CHEASE + XTOR are now in a reasonable state to start work
- CHEASE is used as if reading experimental data from EXPEQ
- This improvement should be done in parallel with Guillaume Brochard's EPCOM particle distribution initialization

Simulation example 1: 2-fluid sawtoothing, initial conditions



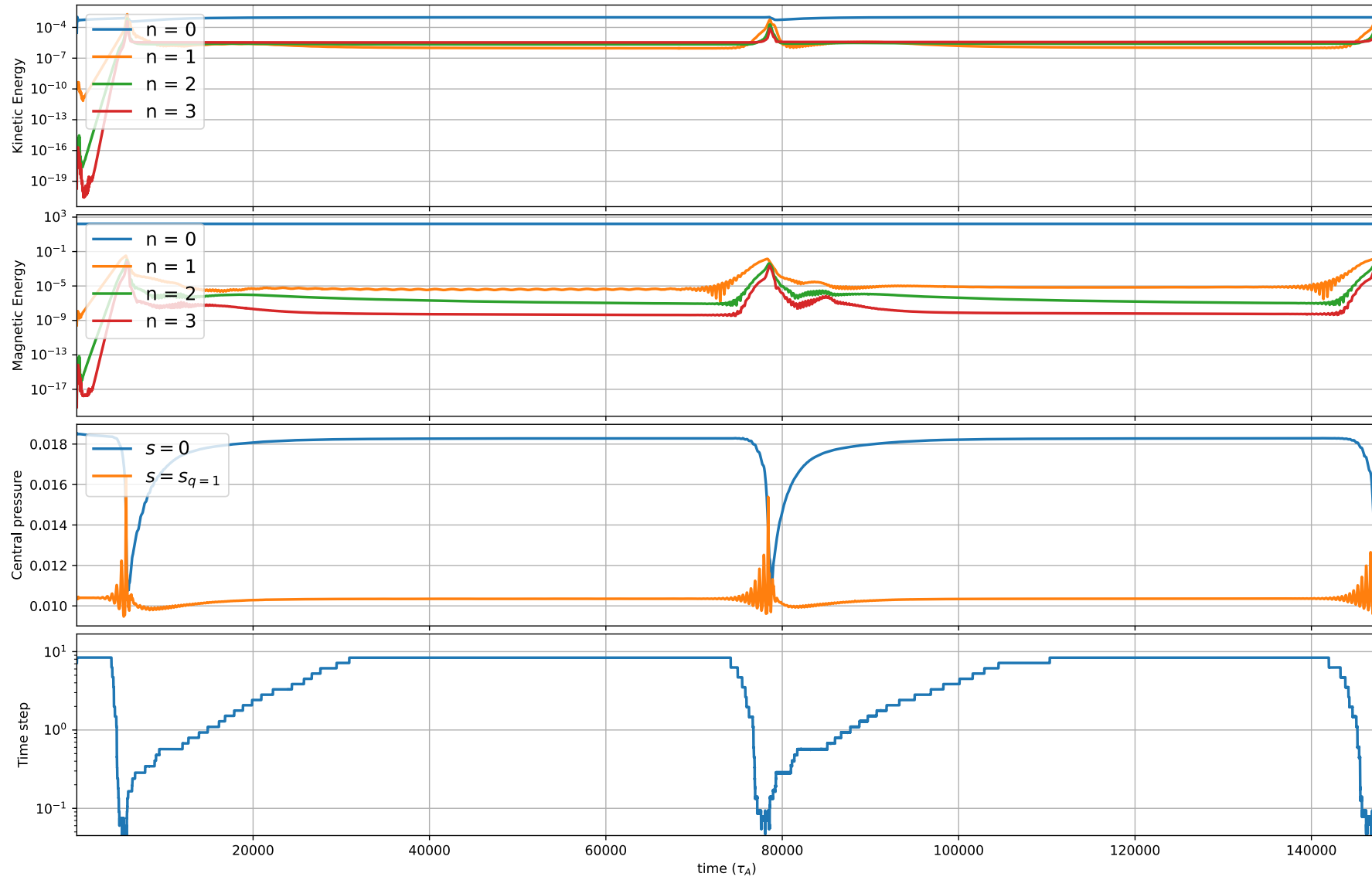
Halpern et al, Phys.Plasmas **18**, (2011) 102501



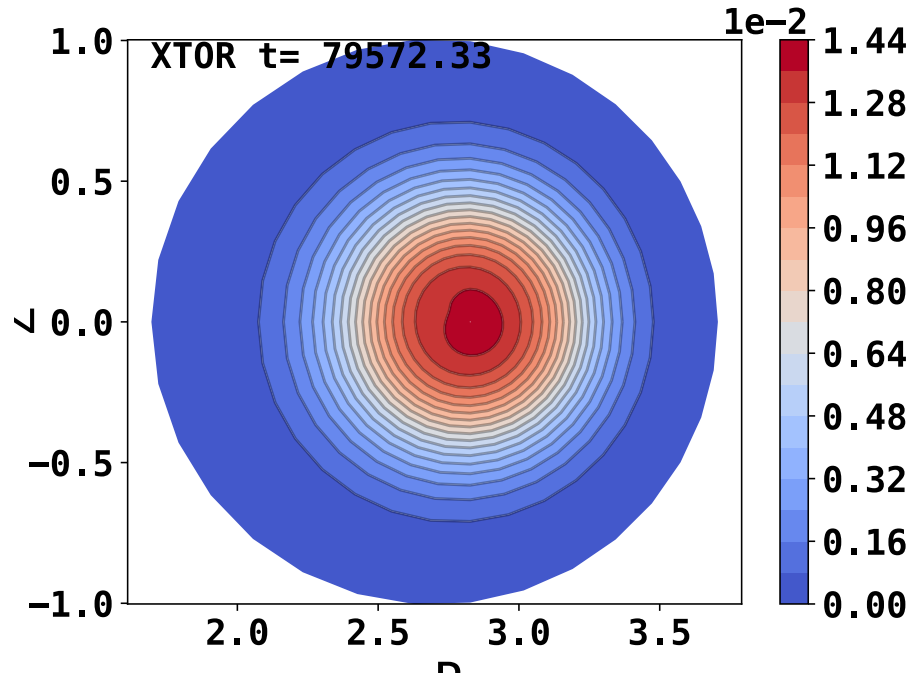
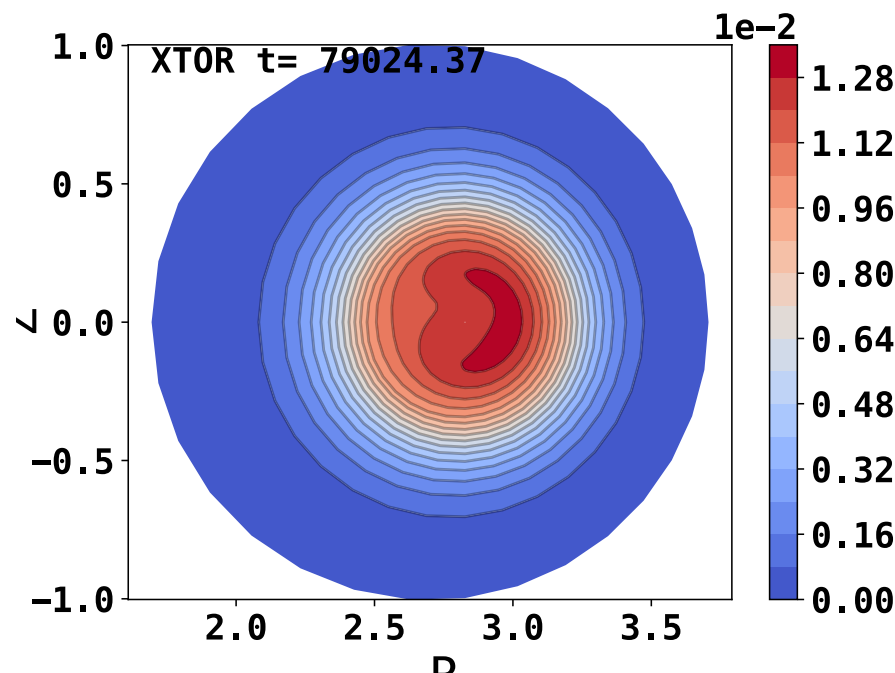
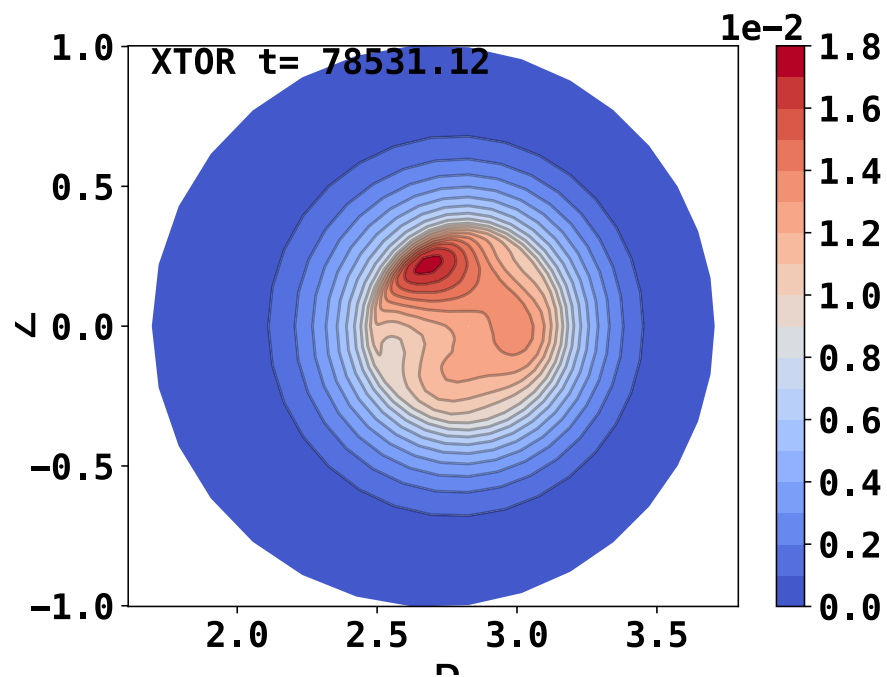
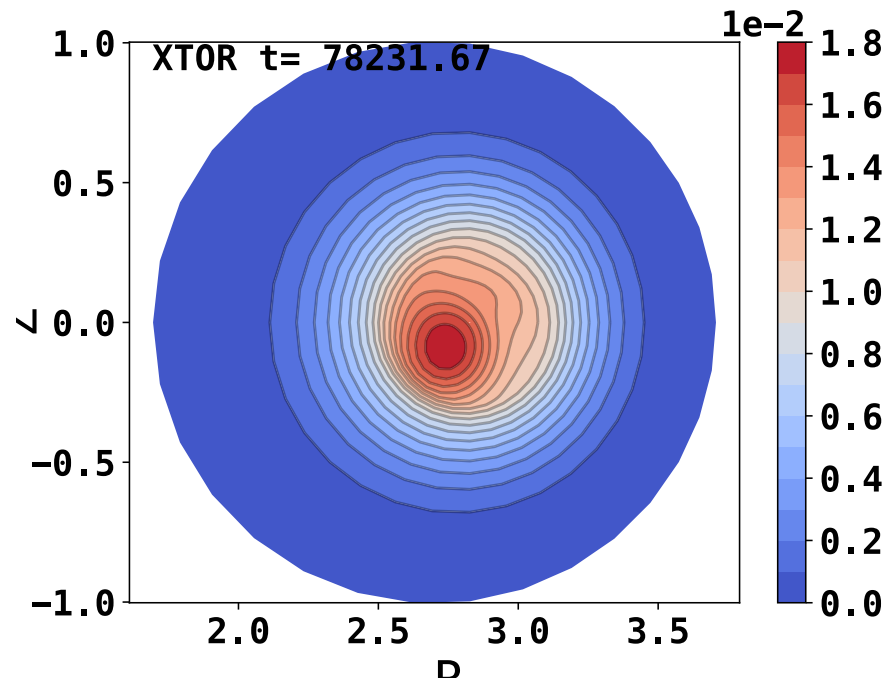
$$S = 10^7$$

$$\alpha = (\omega_{ci} \tau_a)^{-1} = 0.15$$

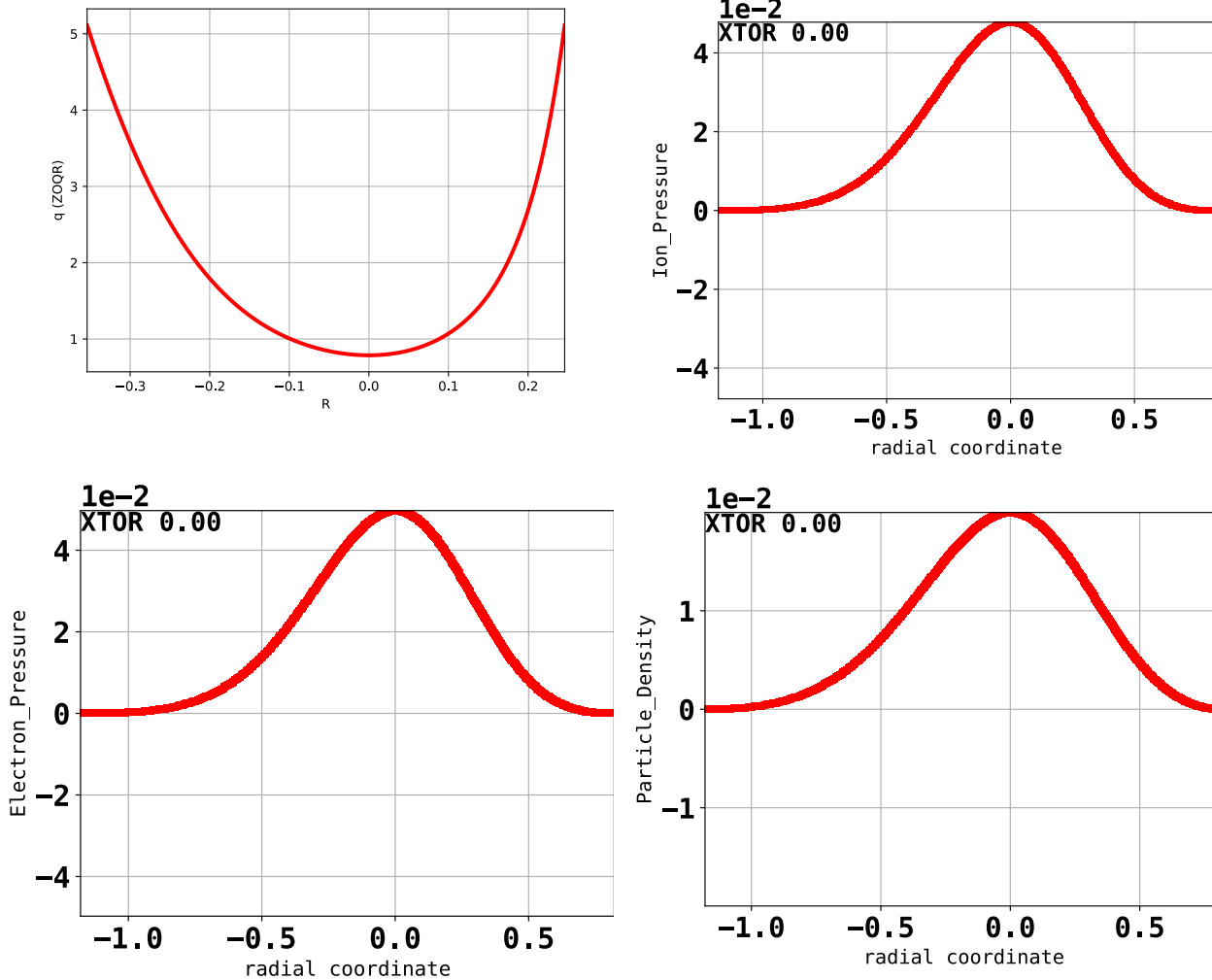
Simulation example 1: 2-fluid sawtoothing, time evolutions



Simulation example 1: 2-fluid sawtoothing, pressure evolution during crash



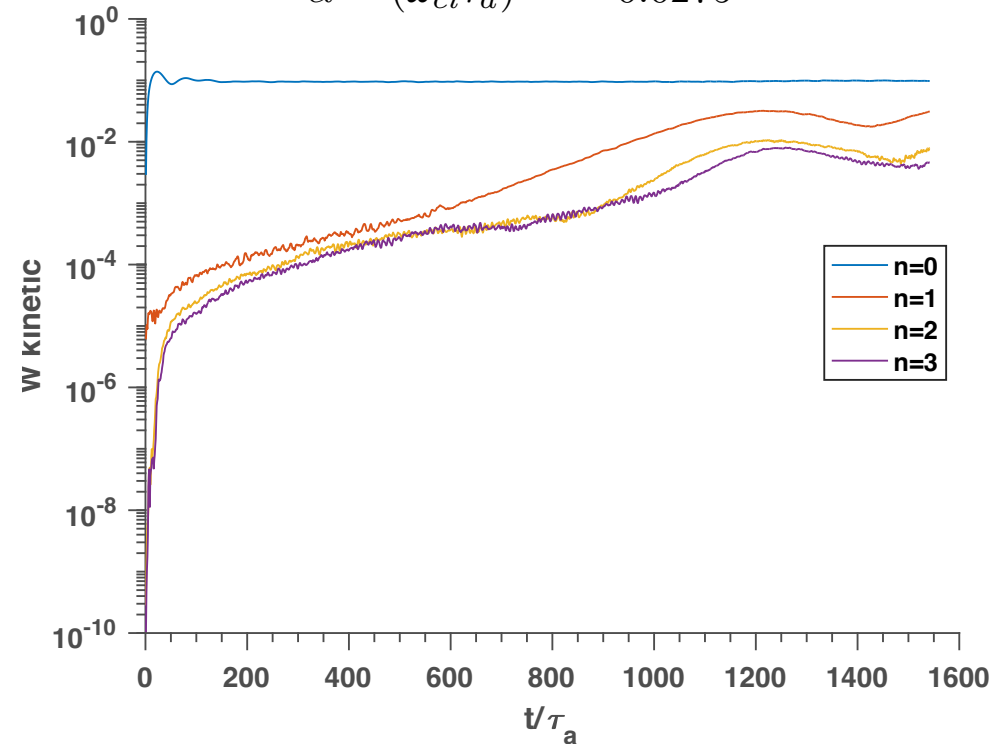
Simulation example 2: Internal kink simulation (MHD+alphas)



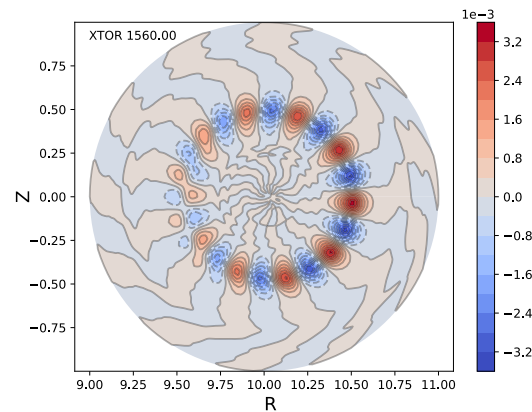
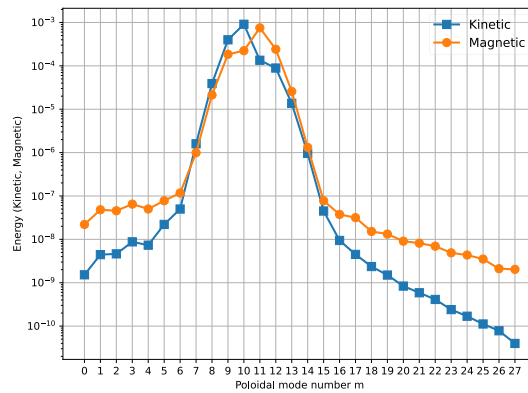
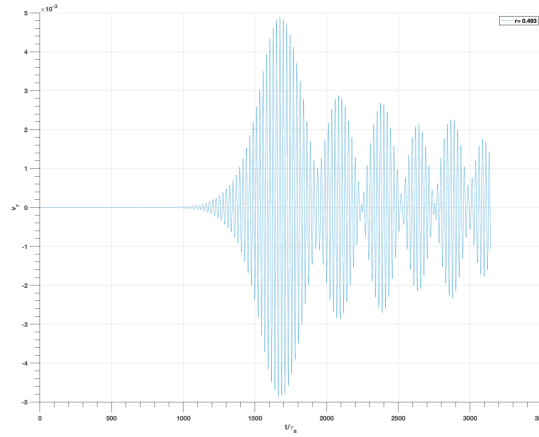
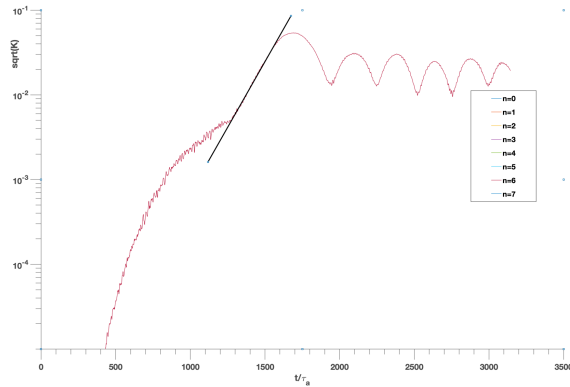
Ni0=ne0=2 10^{19} m⁻³
Ti0=Te0=30KeV
Nf0=4. 10^{17} m⁻³
Alpha's of 3.5 MeV (Maxwellian)

$$S = 10^6$$

$$\alpha = (\omega_{ci}\tau_a)^{-1} = 0.0275$$



Simulation example 3: ITPA/Mishchenko TAE test case)



n=6 TAE evolution:

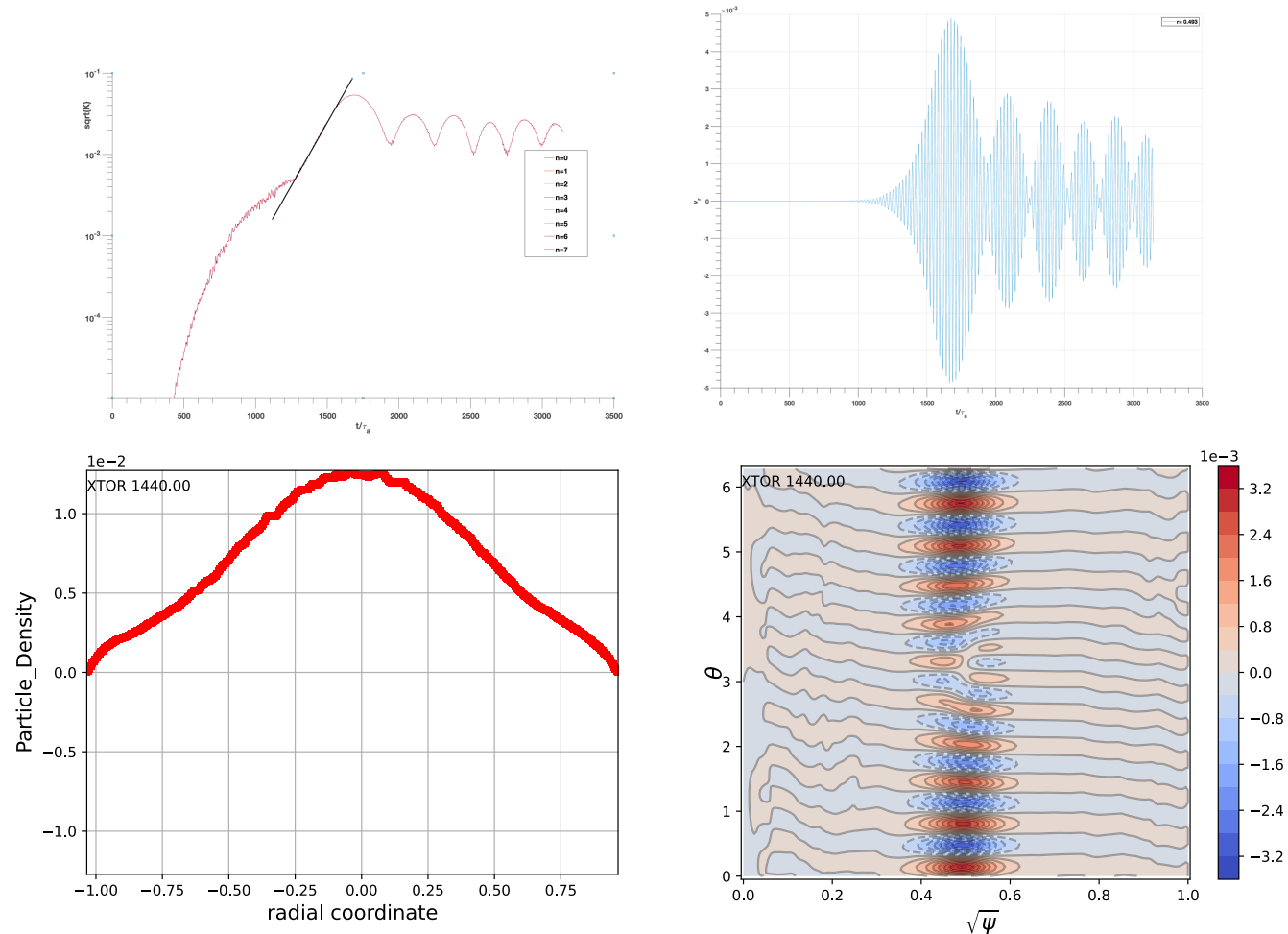
$\Gamma = 2.18 \times 10^4 \text{ s}^{-1}$
 $\Omega = 0.399 \times 10^6 \text{ rad/s}$

Compares well with
[Mishchenko 2009, Könies 2018]:

$\Gamma = 2.3 \times 10^4 \pm 10\% \text{ s}^{-1}$
 $\Omega = 0.42 \times 10^6 \text{ rad/s}$

Omega ideal MHD eigenvalue
code (CAS3D):
 $\Omega = 0.401 \times 10^6 \text{ rad/s}$

Simulation example 3: ITPA/Mishchenko TAE test case)



n=6 TAE evolution:

$$\begin{aligned}\Gamma &= 2.18 \times 10^4 \text{ s}^{-1} \\ \Omega &= 0.399 \times 10^6 \text{ rad/s}\end{aligned}$$

Compares well with
[Mishchenko 2009, Könies 2018]:

$$\begin{aligned}\Gamma &= 2.3 \times 10^4 \pm 10\% \text{ s}^{-1} \\ \Omega &= 0.42 \times 10^6 \text{ rad/s}\end{aligned}$$

Loss of 25% of the kinetic ions:

-> Would be good to compare with a vanishing K-density case at plasma edge

Ongoing and future work

1) On the more technical side:

- 2 ACH projects : GPU migration becomes more and more urgent. GPU machines (in France) have politically the priority and power supply is finite in HPC centers. IMASification is mandatory.
- Re-up the GC pusher. In principle OK but needs some testing.
- I will spend time to publish the code, probably as CHEASE in the CPC code library is the best option. But tedious and long work.
- Last but no least, the code has a problem in Cray environment. Easy solution: avoid Cray's... But I dislike this option.

2) On the side of physics:

- Starting the sawtooth simulations with a fusion alpha population. The code is shaped for this now.
- The free boundary version of the code starts to give results, which open new perspectives.