Status of AE-kink simulations using XTOR

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Outline

- Fast presentation of XTOR-K
- ITPA TA simulation
- Mishchenko internal kink simulation
- Nonlinear hybrid internal kink with 2 MeV alphas

XTOR-K fluid equations

$$\partial_t(\sum_{s=i,k} m_s n_s \mathbf{u}_s) = \mathbf{J}\times\mathbf{B} - \sum_{s=i,e}\nabla p_s - \sum_{s=i,e}\nabla.\mathbf{\Pi_s} - \sum_k \nabla.\mathbf{P_k} = 0$$

$$\partial_t\mathbf{B} = -\nabla\times\mathbf{E}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} - \frac{1}{en_e}\hat{\mathbf{b}}(\hat{\mathbf{b}}.\nabla p_e)) + \frac{\mathbf{J}_\parallel}{\sigma_\parallel} + \frac{\mathbf{J}_\perp}{\sigma_\perp}$$

$$\partial_t n_i = -\nabla.\left(n_i(\mathbf{v}+\mathbf{v}_i^*) - D_\perp\nabla n_i + D_\perp\nabla n_{i,0}\right)$$

$$\frac{DS_s}{Dt} + \frac{\nabla.\mathbf{Q}_s}{p_s} = 0$$

$$S_s = \ln\frac{T_s^{1/(\Gamma-1)}}{n_s} = \frac{1}{\Gamma-1}\ln\frac{p_s}{n_s^\Gamma}, \text{ and } \mathbf{Q}_s = \frac{5}{2}\frac{p_s}{q_s}\frac{\mathbf{B}}{B^2}\times\nabla T_s$$

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

$$D/Dt = \partial_t + \mathbf{u}_s.\nabla$$

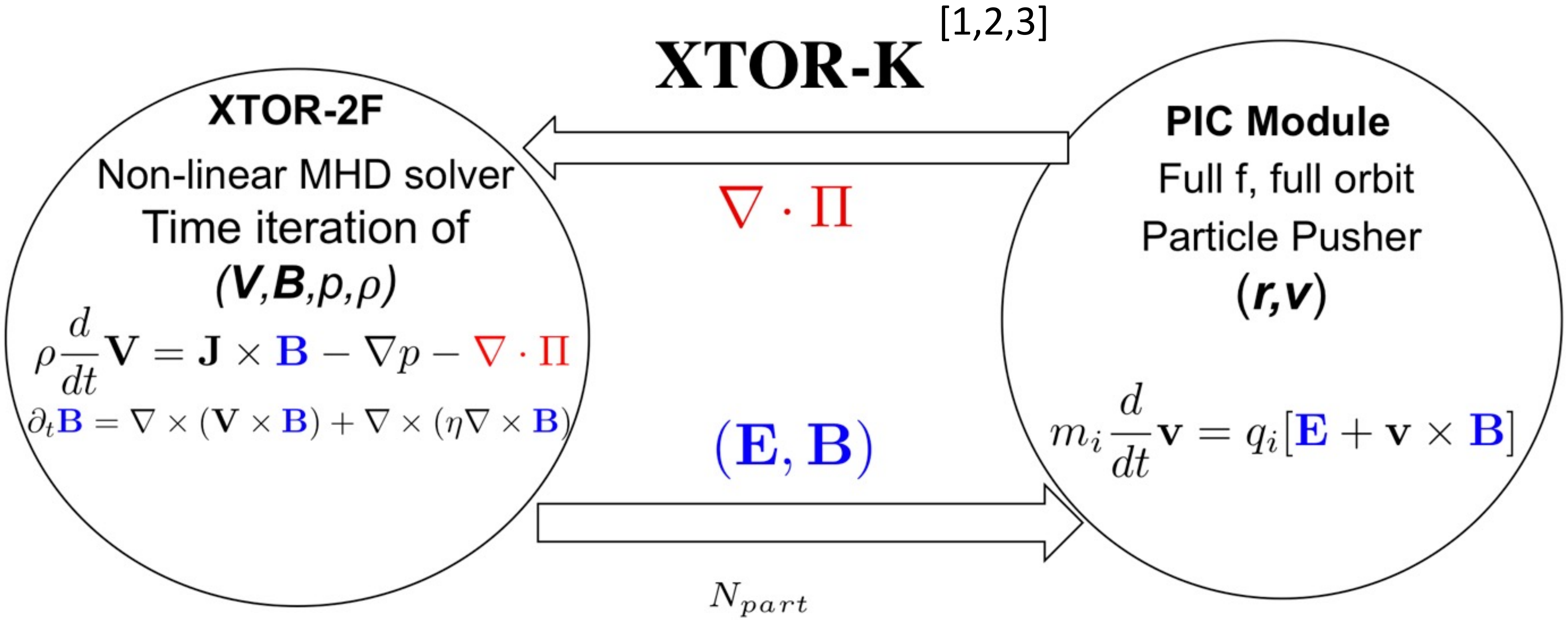
$$\mathbf{u}_s = \mathbf{v}_{s,\parallel} + \mathbf{v}_{\perp,s}^{(1)} + \mathbf{v}_{\perp,s}^{(2)}$$

$$\mathbf{v}_{s,\parallel} = v_{s,\parallel}\hat{\mathbf{b}} = (\hat{\mathbf{b}}.\mathbf{u}_s)\hat{\mathbf{b}}$$

$$\mathbf{v}_{\perp,s}^{(1)} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{\mathbf{B}\times\nabla p_s}{n_s q_s B^2}$$

KINETIC-MHD HYBRID CODE XTOR-K

[1] *H. Lütjens et al, JCP 2010*
[2] *D. Leblond, PhD thesis 2013*
[3] *G. Brochard, PhD thesis 2019*



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

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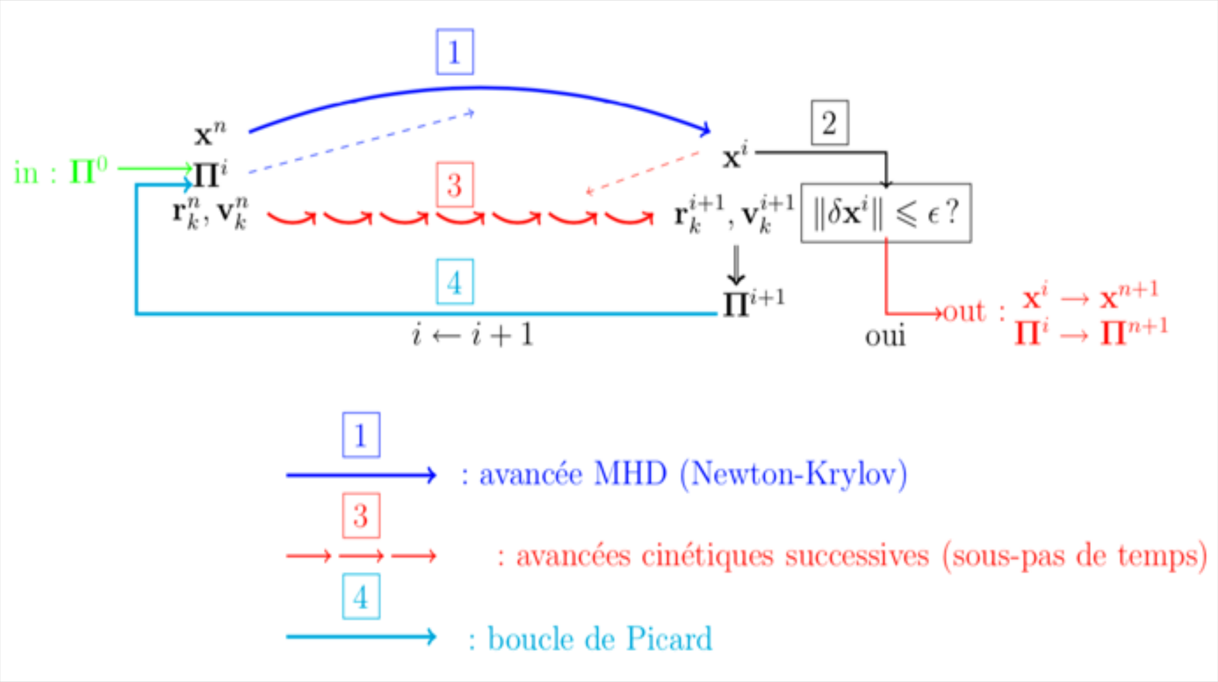
Hybrid scheme



- MHD advance: pre-conditioned Newton Krylov (iterative). Inherited from XTOR-2F (JCP-2010). Physical pre-conditioner
- Kinetic ion advance: Boris Buneman PIC
- Unconditionnaly stable for fluid time steps of interest

Last year:

- Pre-conditioning with a parallel SPIKE-LU solver
- Merge into the hybrid kinetic/fluid environment of the code.
- Newton Krylov using petsc DD features: ready for other families of pre-conditioners (mathematical)

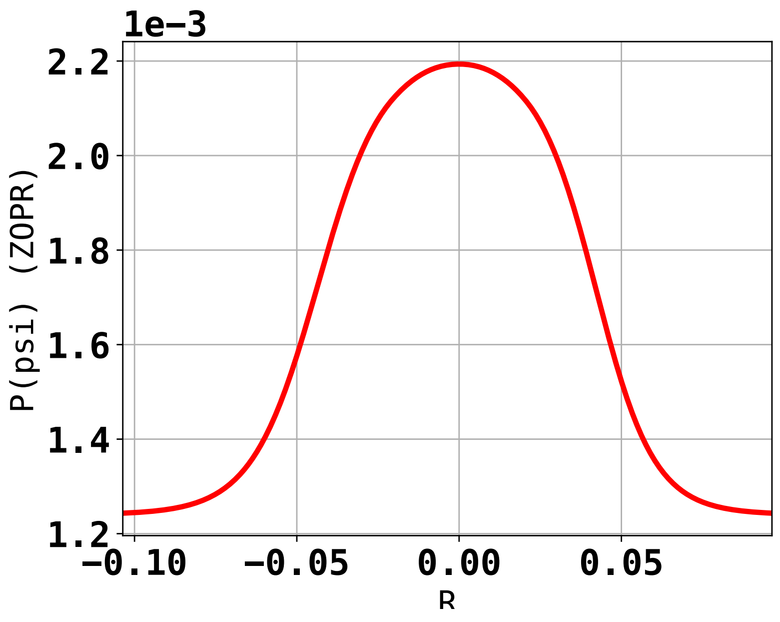
Gains:

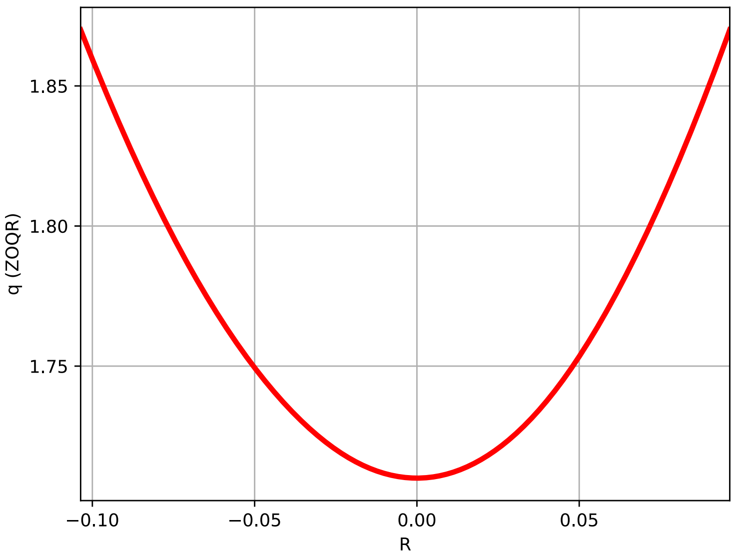
- Factor 2 due to particle sorting (reduces strongly cash missings for moment depositions)
- Factor 2.5 due to the new solver

→ Overall factor of 5 in cpu time and much better global parallelization properties

TAE simulations : Mishchenko TAE test case

- Flat bulk density (ni=ne=2^{E}19m-3) and temperature ion and electron profiles (Ti=Te=1 KeV). Hydrogen ions
- Flat fast ion temperature (Tf=400keV)
- Fast ion density: (nk=0.75^{e}17m-3 at q=1.75). Deuterium ions. Exp(tanh) shape
- CHEASE with fixed q profile
- B0=1T, R_0=10m,A=10





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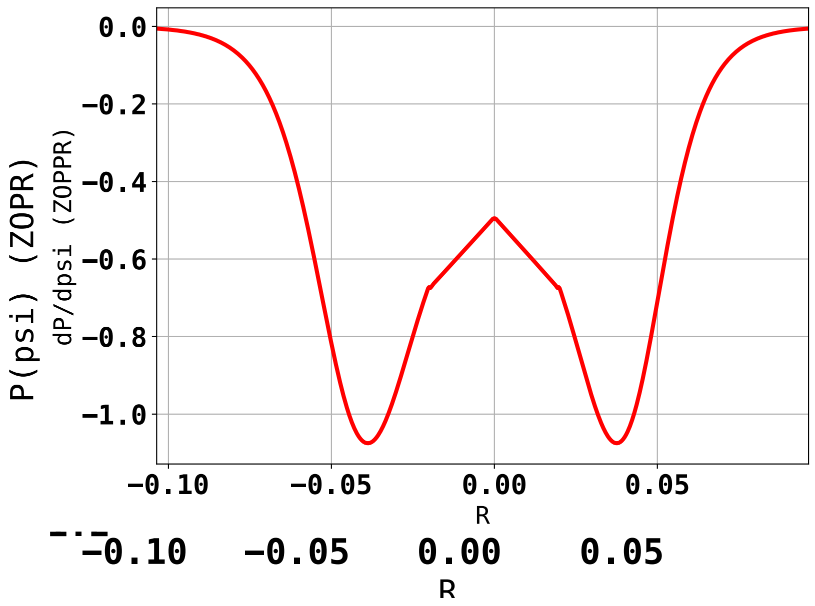
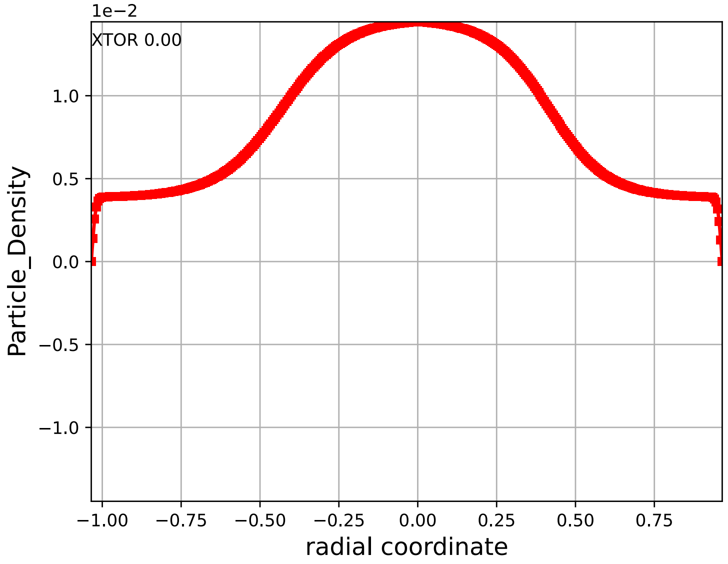
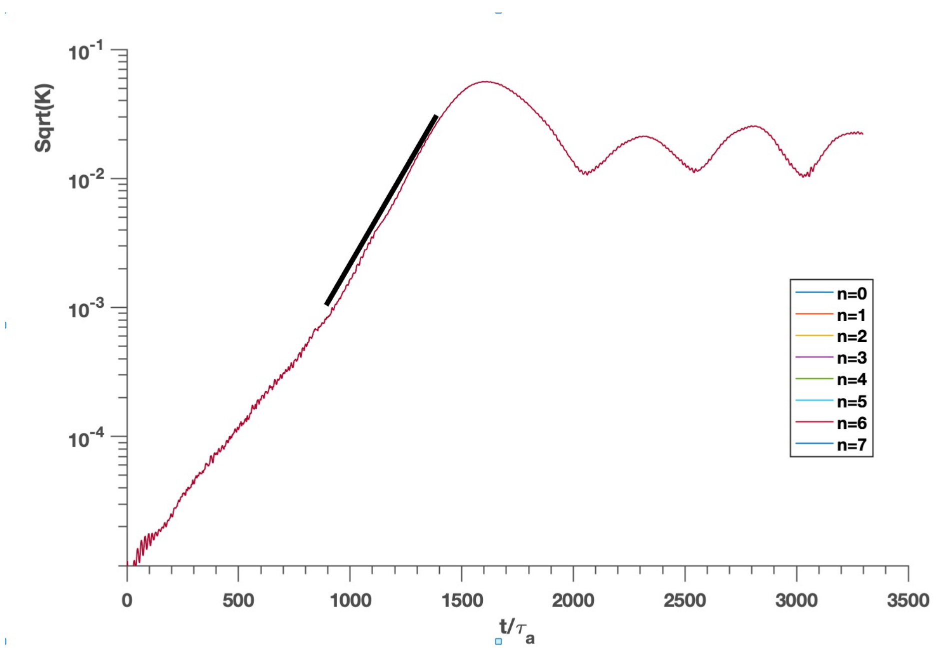
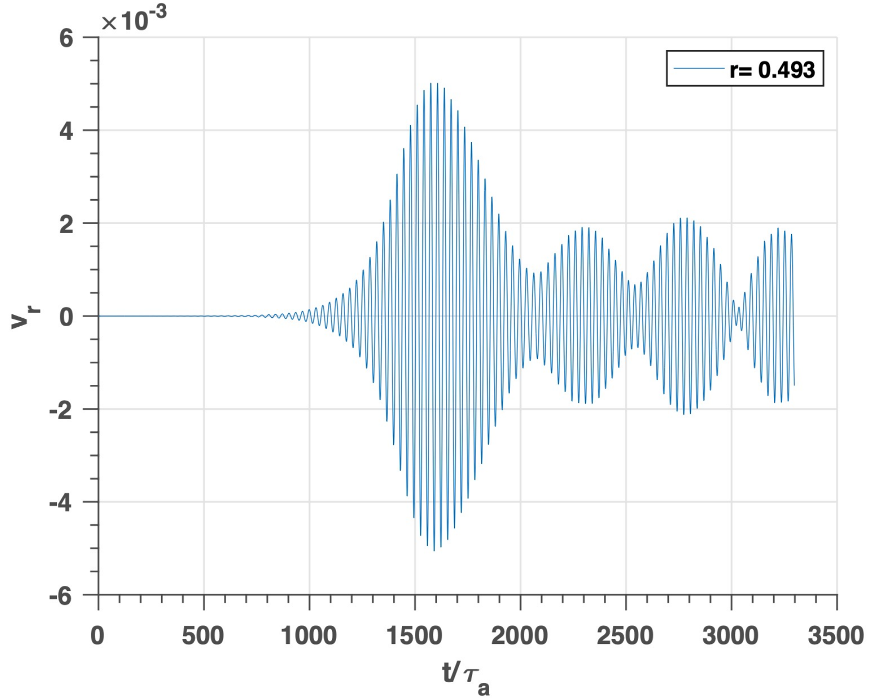
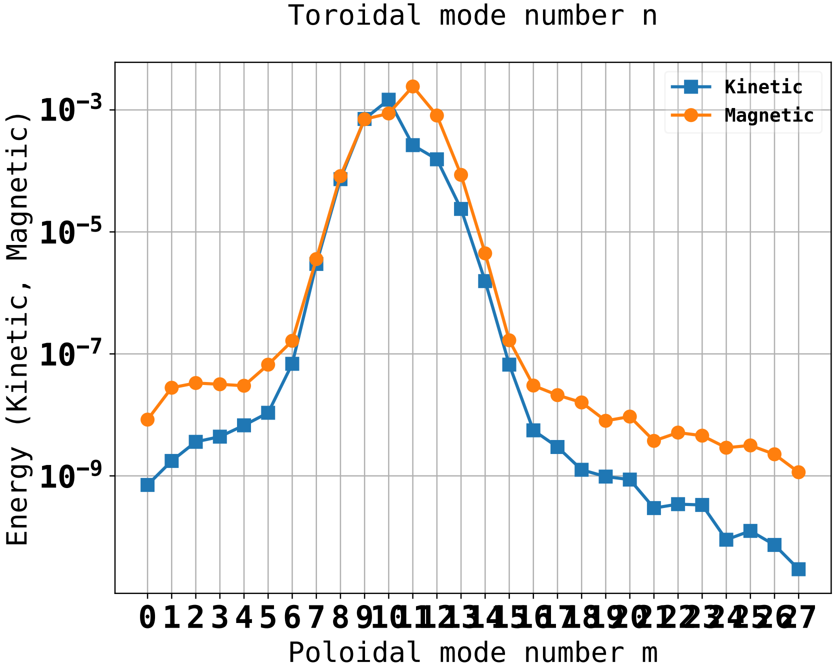
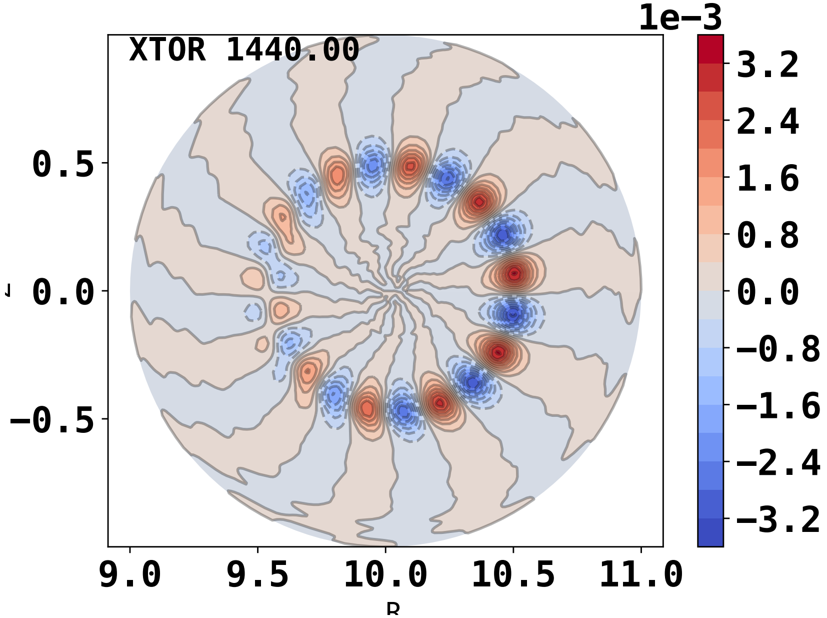












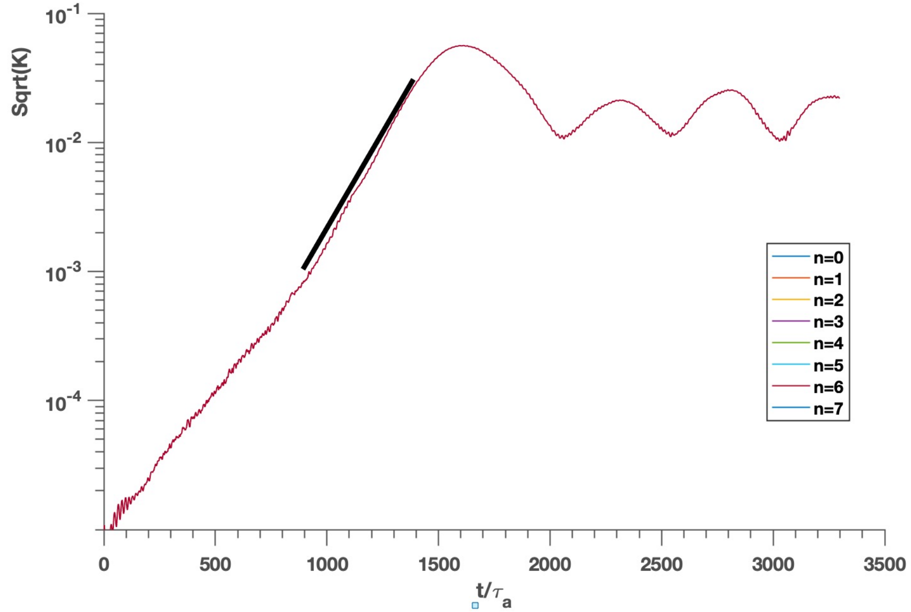
n=6 evolution:

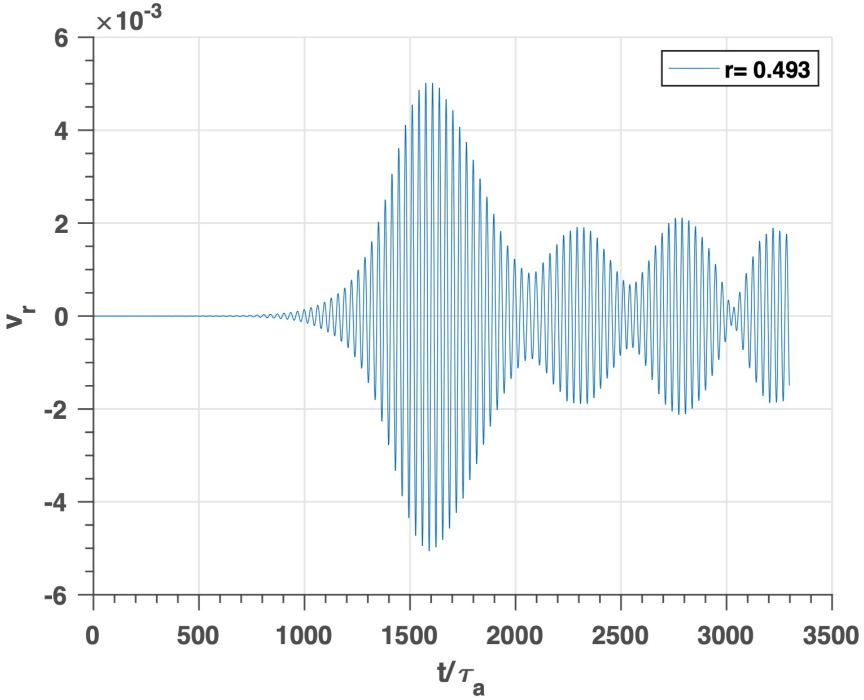
Gamma = 33.3 10^3 rad/s
Omega = 0.296 10^6 rad/s

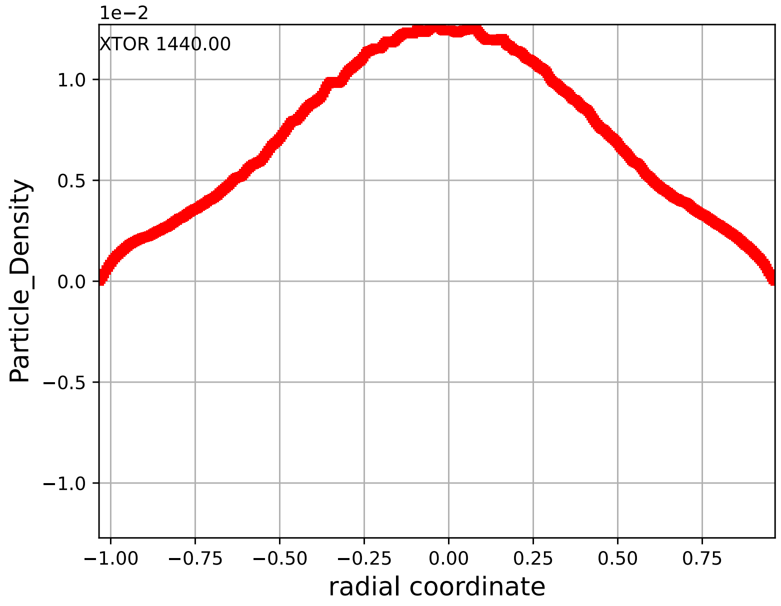
With tau_a = 6.86 10^{-8} s

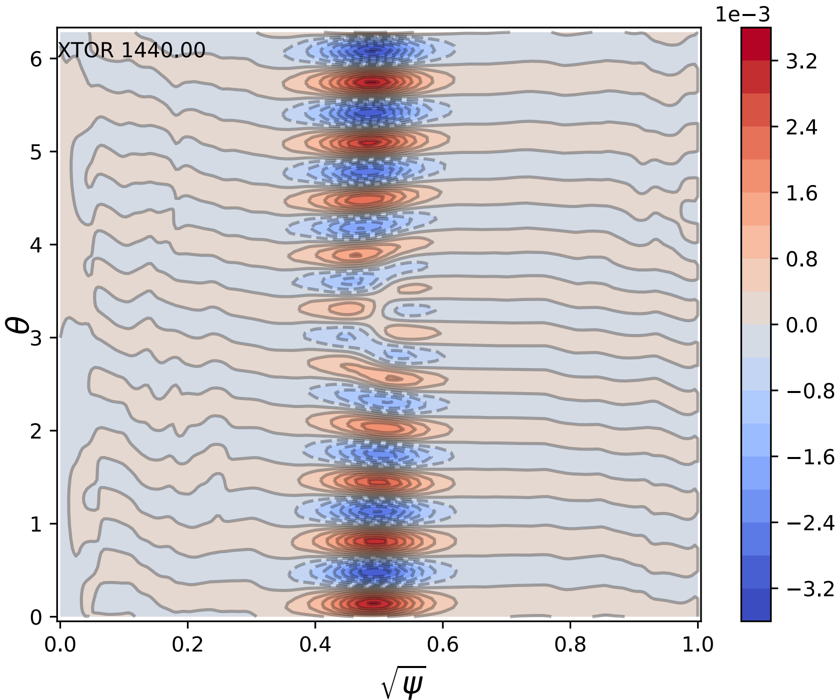
To be compared with (Mishchenko 2009):

Gamma = 20 10^3 rad/s
Omega = 0.43 10^6 rad/s









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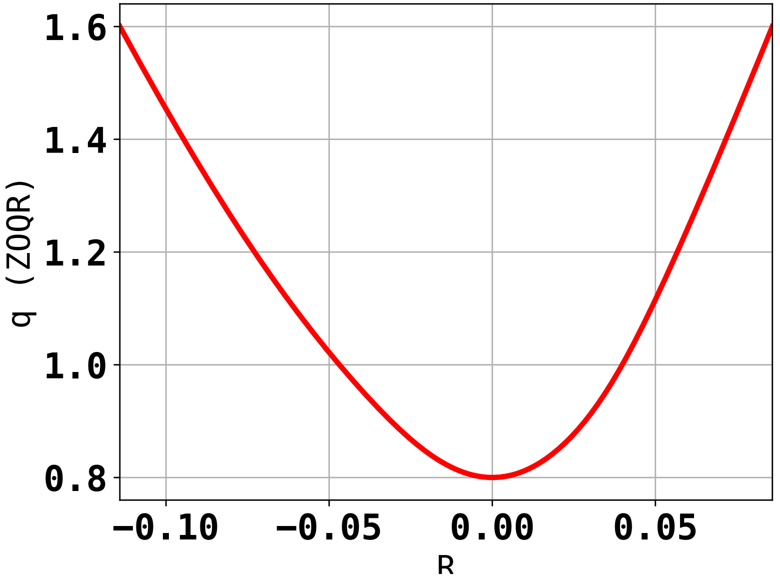
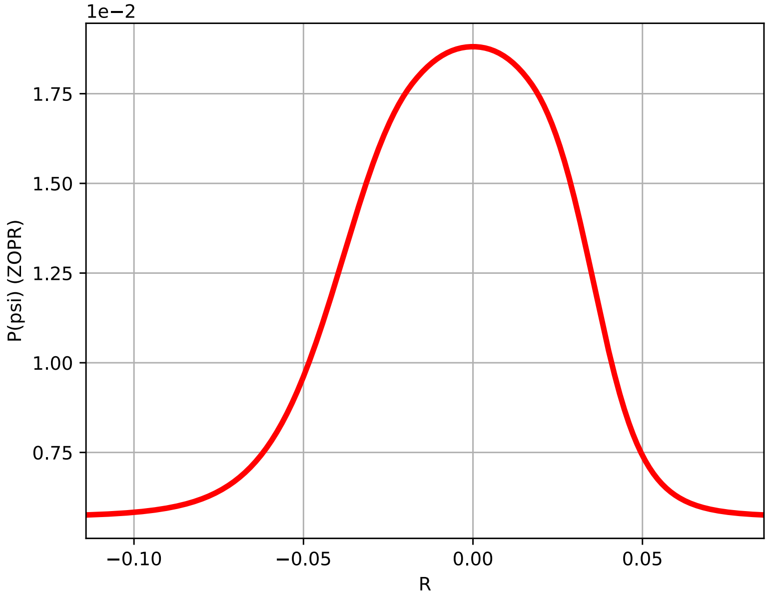
Loss of 25% of the kinetic Ions:

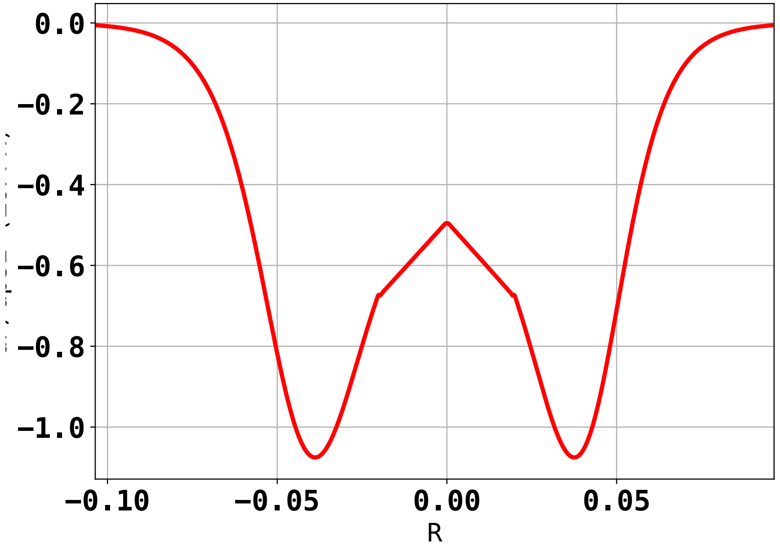
-> Would be good to compare with a vanishing K-density at plasma edge

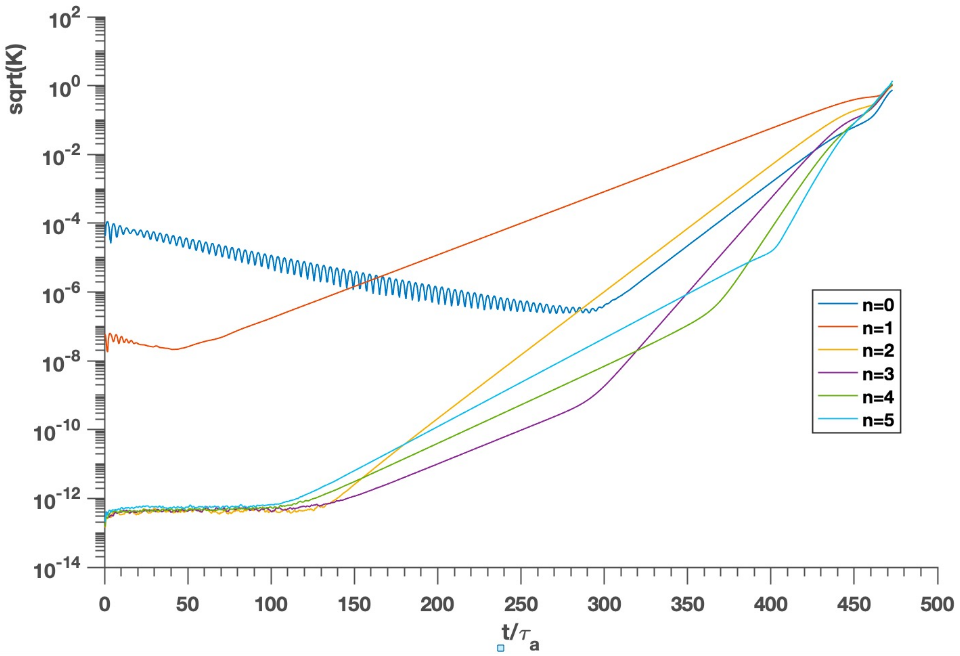
Kink simulations (1) : Mishchenko kink test case

- Flat ion and electron temperature profiles (Ti=Te=2.957 KeV). Hydrogen ions
- bulk density and Exp(tanh) shape: ni (r=0.5)=ne(r=0.5)=8.74^E18m-3
- CHEASE with fixed q profile
- B0=3T, R_0=10m, A=10; beta_pol=3.92





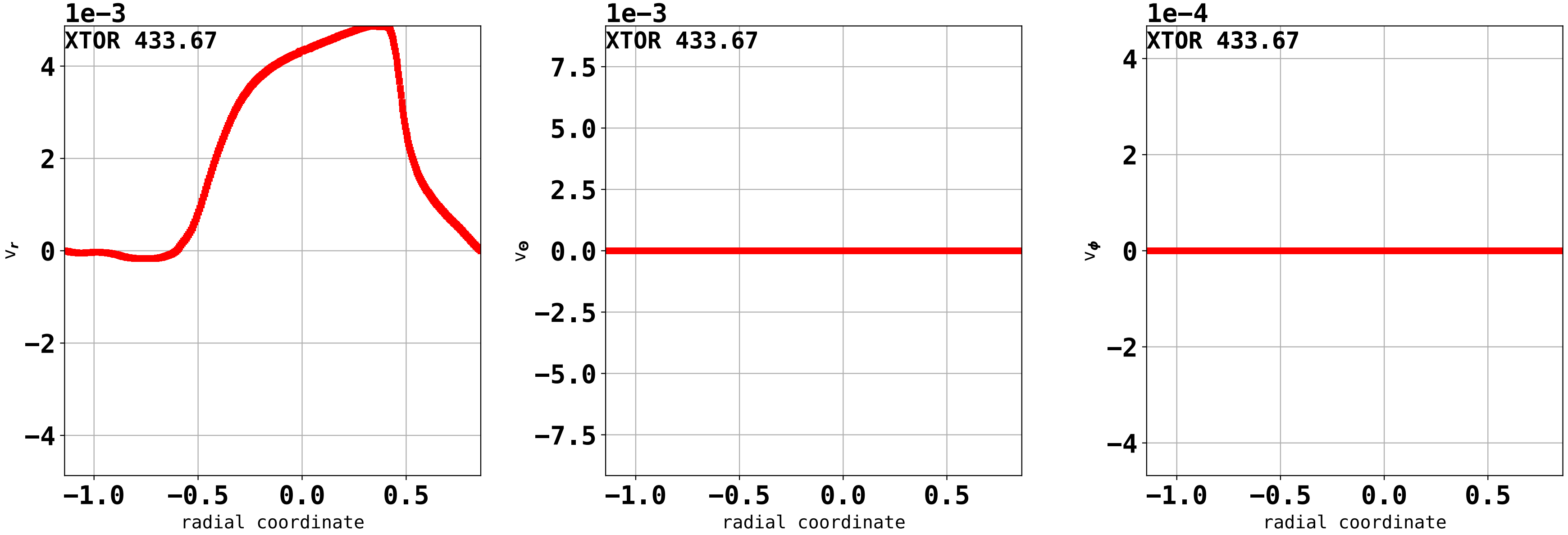


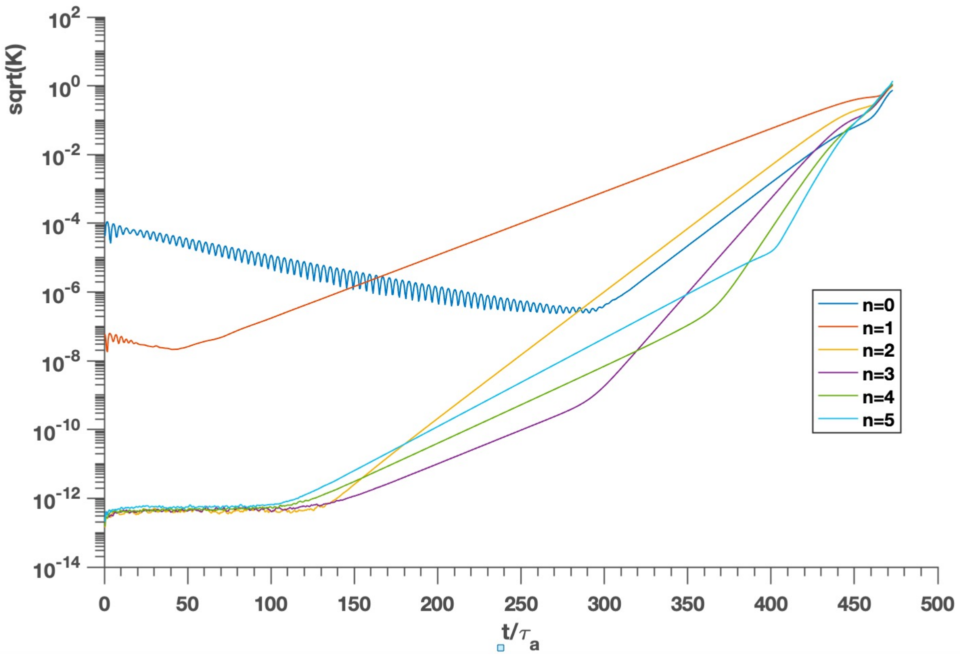


Internal kink evolution:

Gamma = 3.92 10^6 rad/s

With tau_a = 1.35 10^{-7} s





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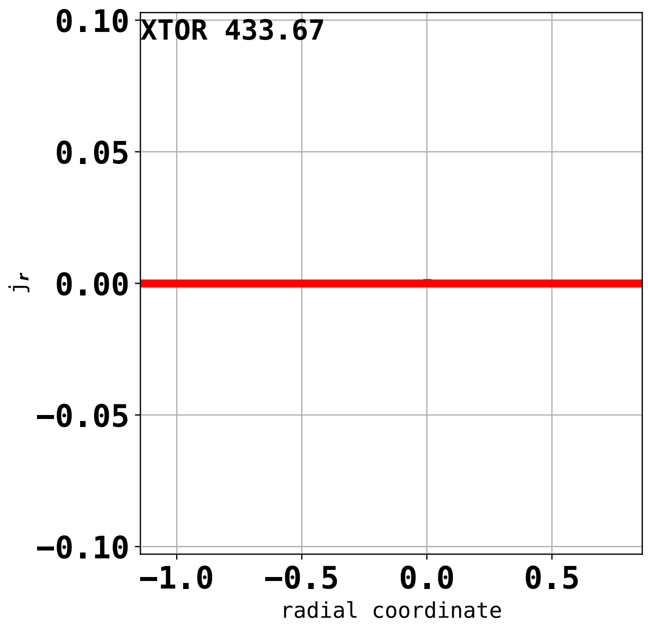

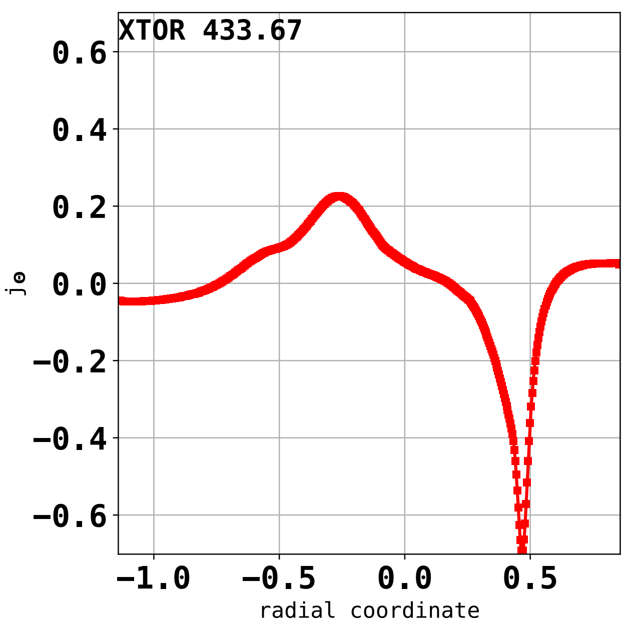

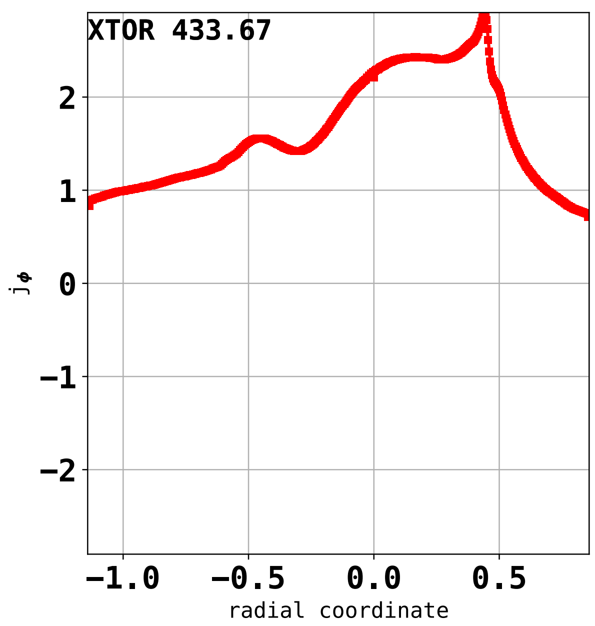

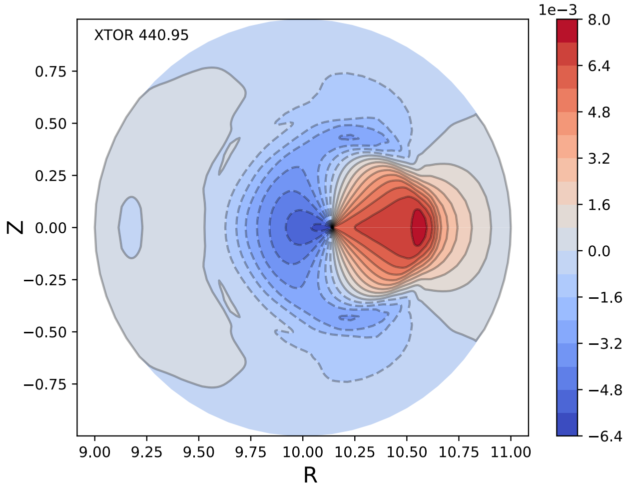

V_r(phi=0)

Internal kink evolution:

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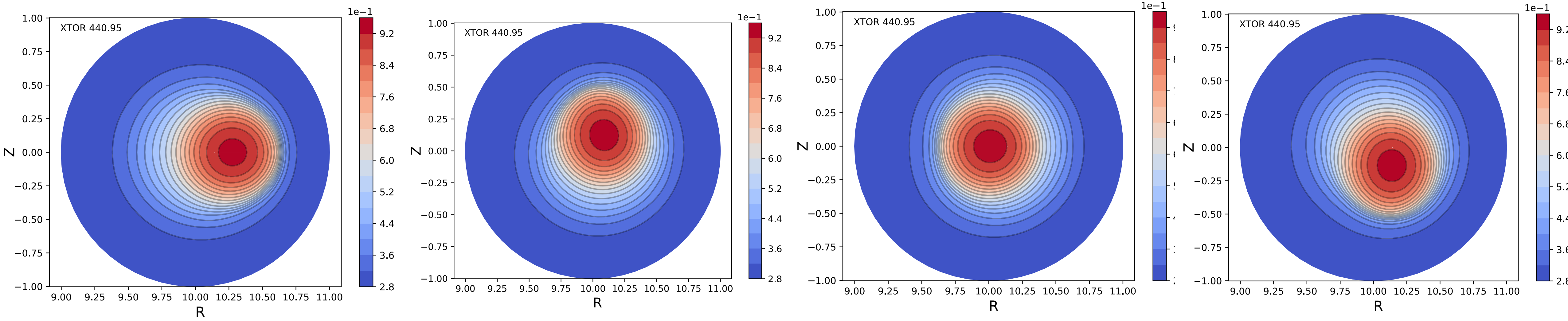
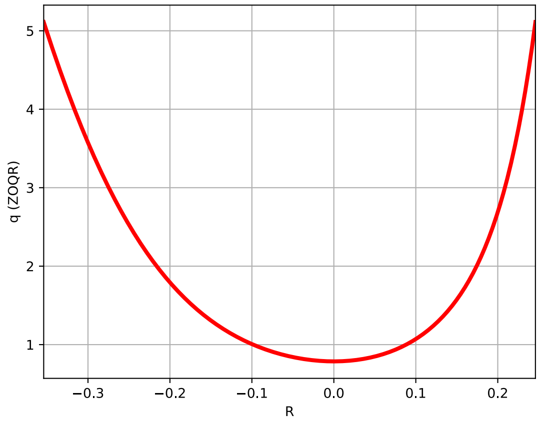
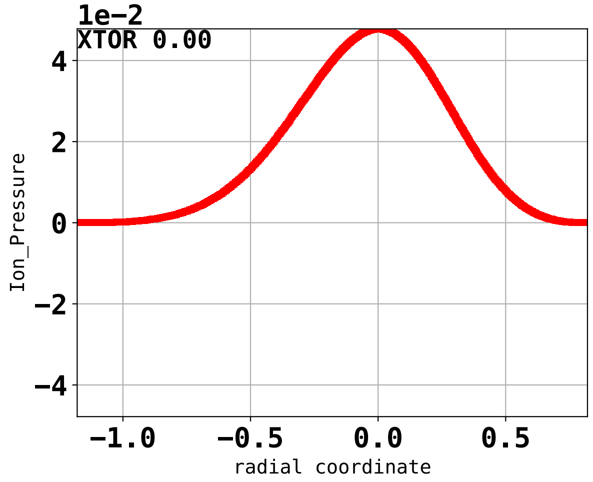
With tau_a = 1.35 10^{-7} s

Electron pressure phi=0,pi/2,pi,3pi/2



Internal kinKink simulations (2) : Hybrid simulation with 2Mev Fusion alphas





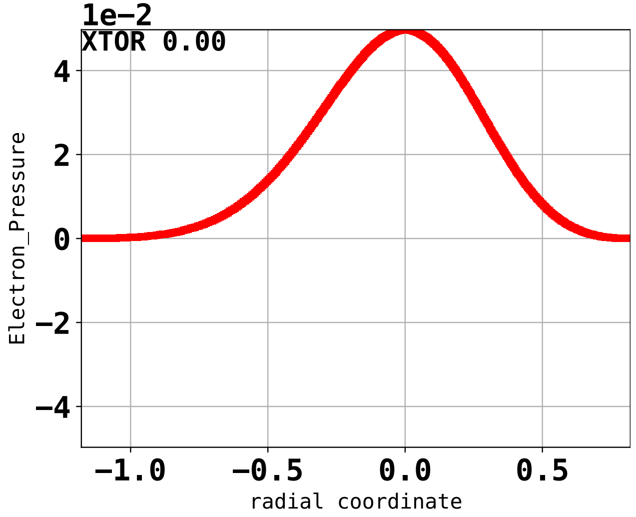
Ni0=ne0=2 10^19 m-3

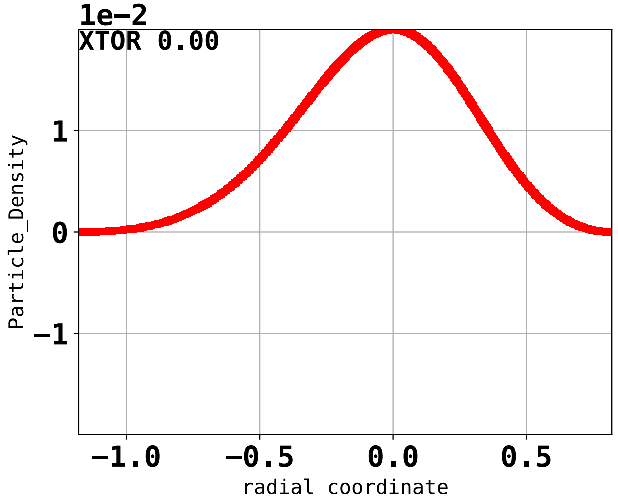
Ti0=Te0=30KeV

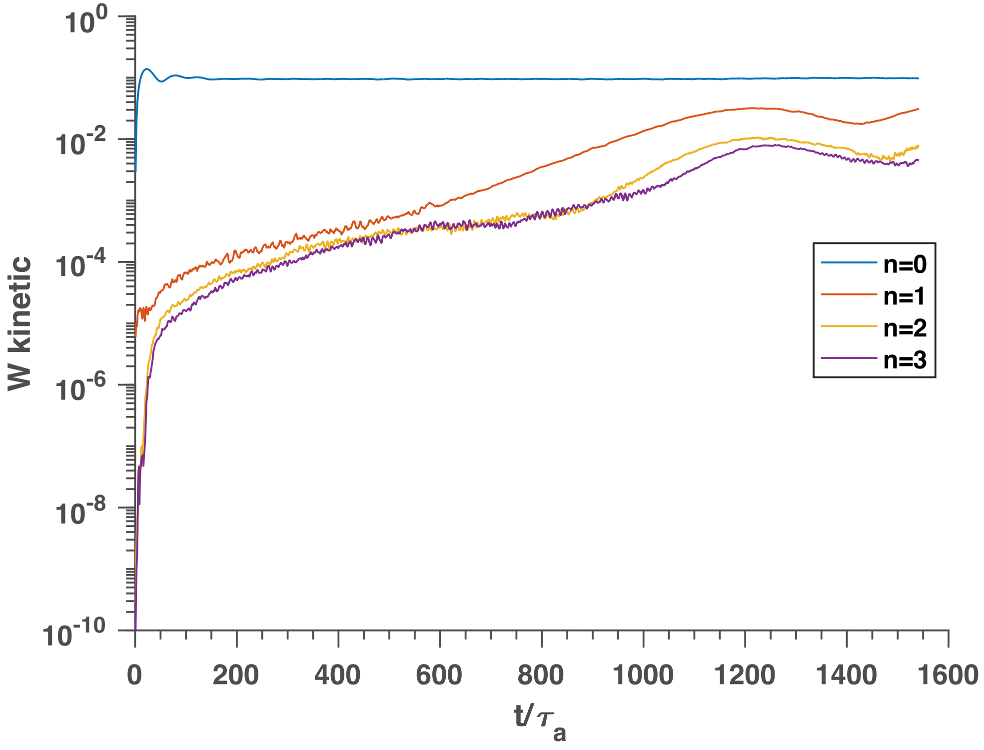
Nf0=4.10^17 m-3

Beta_pol=0.78;

r(q=1)=0.45







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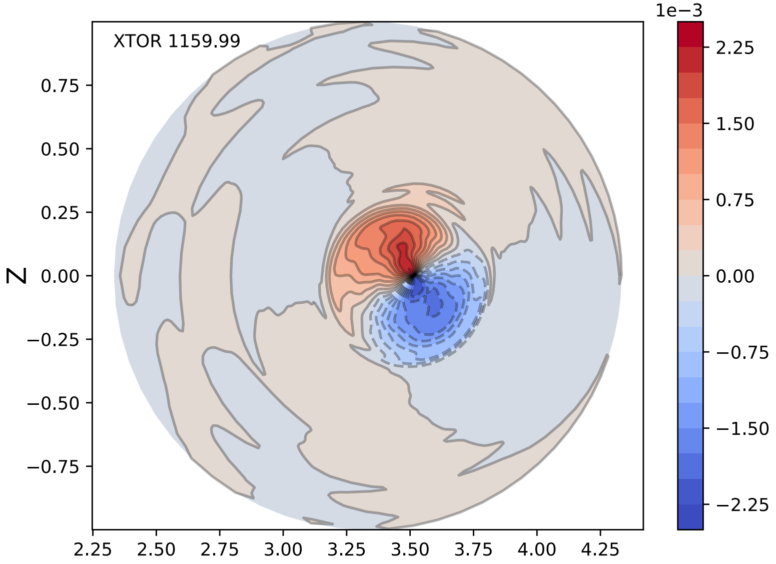
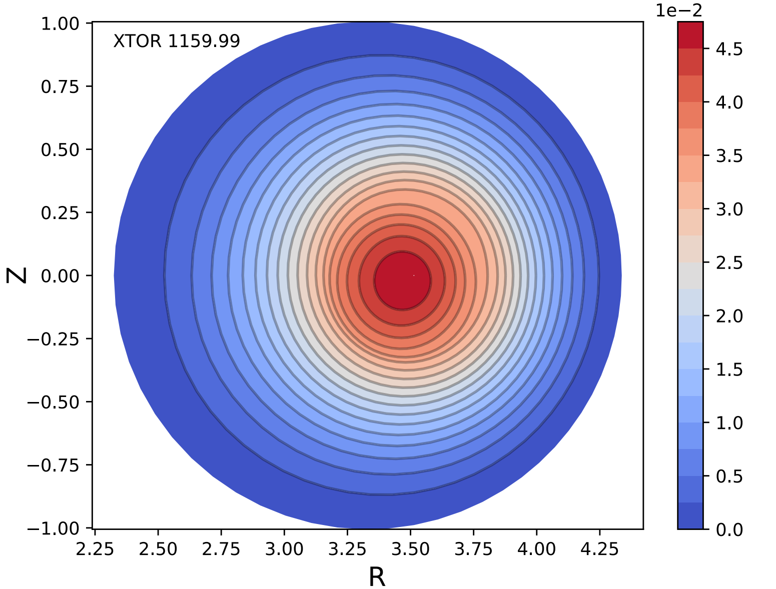
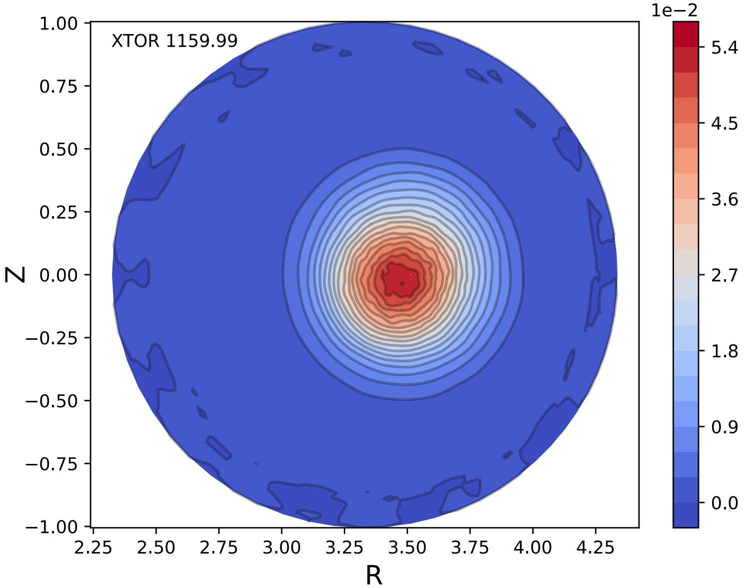


V_r(phi=0)

Ni0=ne0=2 10^19 m-3
Ti0=Te0=30KeV
Nf0=4.10^17 m-3
Beta_pol=0.78;
r(q=1)=0.45
S=3.e6
Chi//=1., Chi_perp=1.e-6

Fluid and kinetic ion pressures



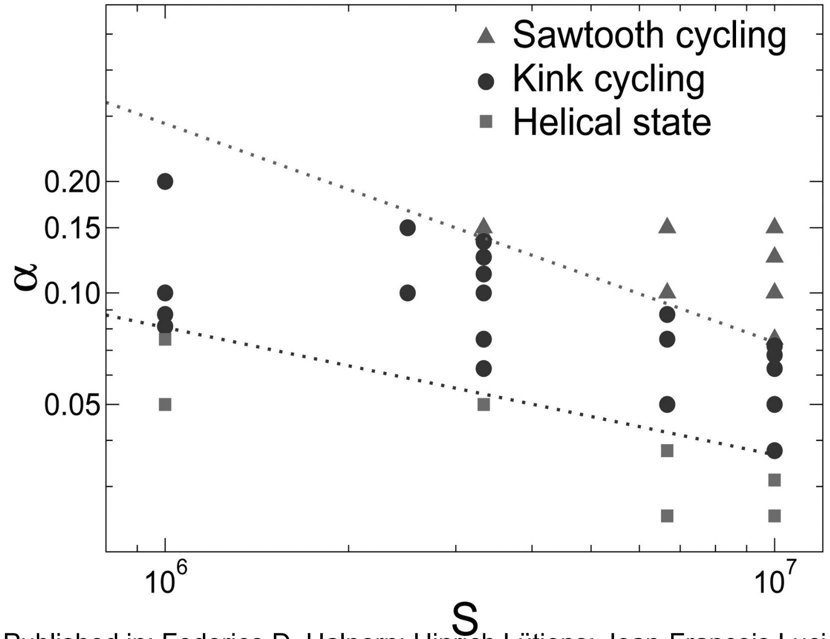


Comparison with 2-fluid sawtooth simulations:

3 regimes:
- Saturated helical m=n=1 equilibrium
- Oscillating kinks
- Sawtooth

In the hybrid siumulation, S=3.e6
Fluid alpha = 0.

-> We are in the **saturated kink regime**



Cyclic regimes found as a function of $\alpha = (\omega_{ci}\tau_a)^{-1}$ and $S = 1/\eta$.

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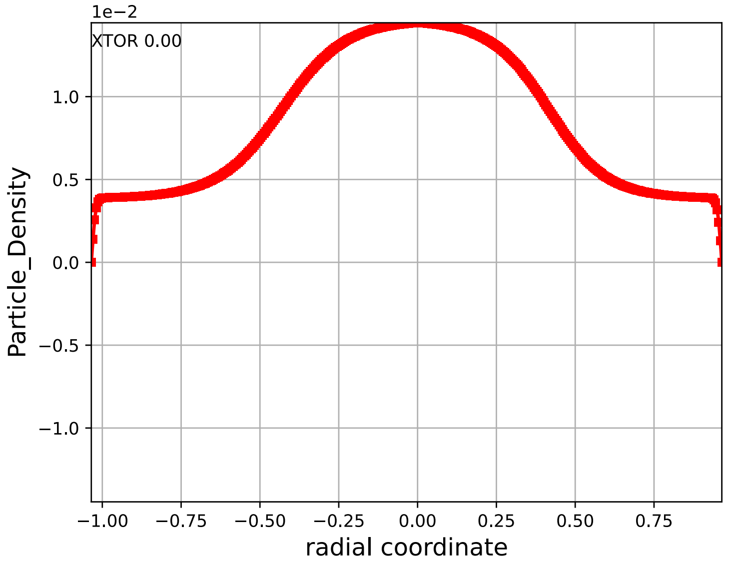
DOI: 10.1063/1.3646305

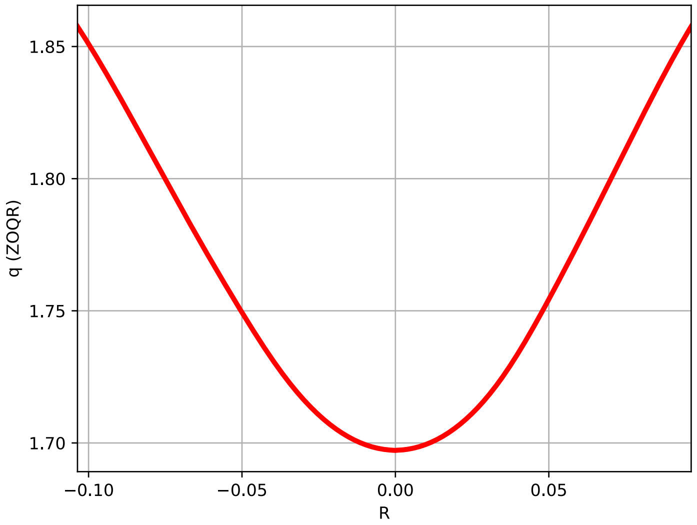
Open work

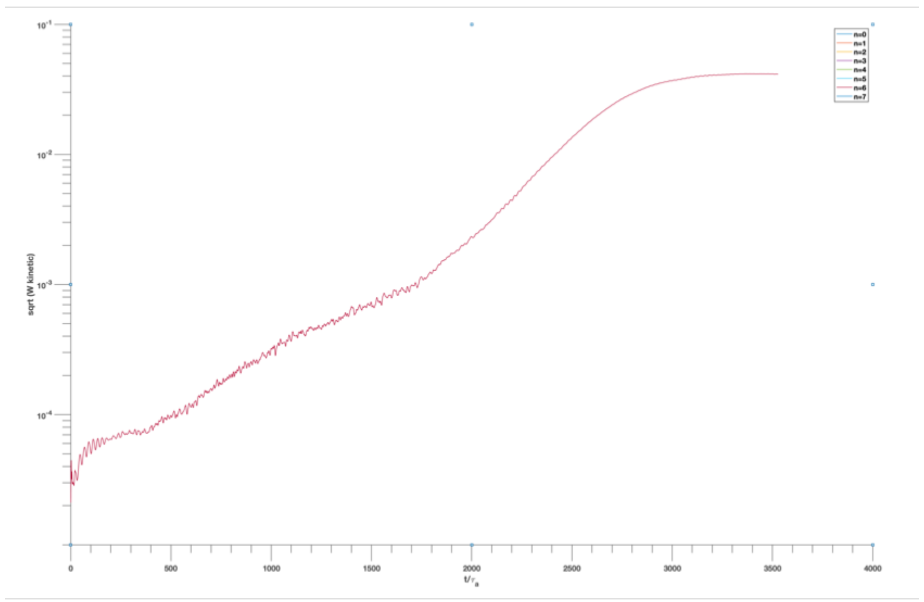
- Benchmarks with vanishing kinetic ion density profiles for a more detailed comparison
- Moving towards sawtoothing regime. Needs complete fluid model and fluid/kinetic connection
- Update of NBI beam injectors (Started with pdoc F. Orain)
- Upgate GC particle pusher
- Finish version with equilibrium separatrix and vacuum

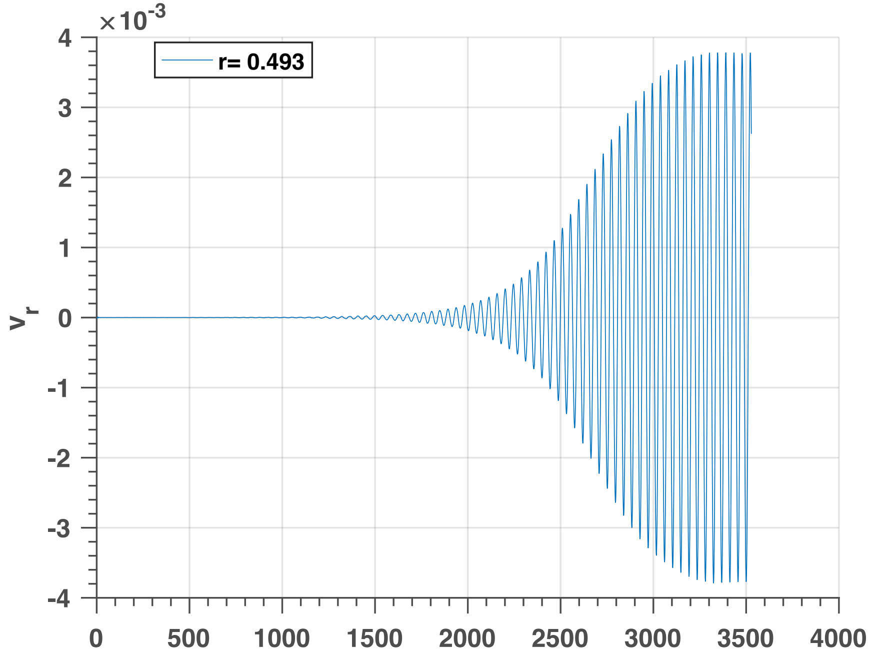
TAE simulations : Mishchenko TAE test case

- Flat bulk density (ni=ne=2^{E}19m-3) and temperature ion and electron profiles (Ti=Te=1 KeV). Deuterium ions
- Flat fast ion temperature (Tf=400keV)
- Fast ion density: (nk=0.75^{e}17m-3 at q=1.75). Deuterium ions









Gamma = 5.21 10^3Hz
Omega=0.21 10^6 rad/s