Upgrades of XTOR-K for hybrid long time internal instability simulations

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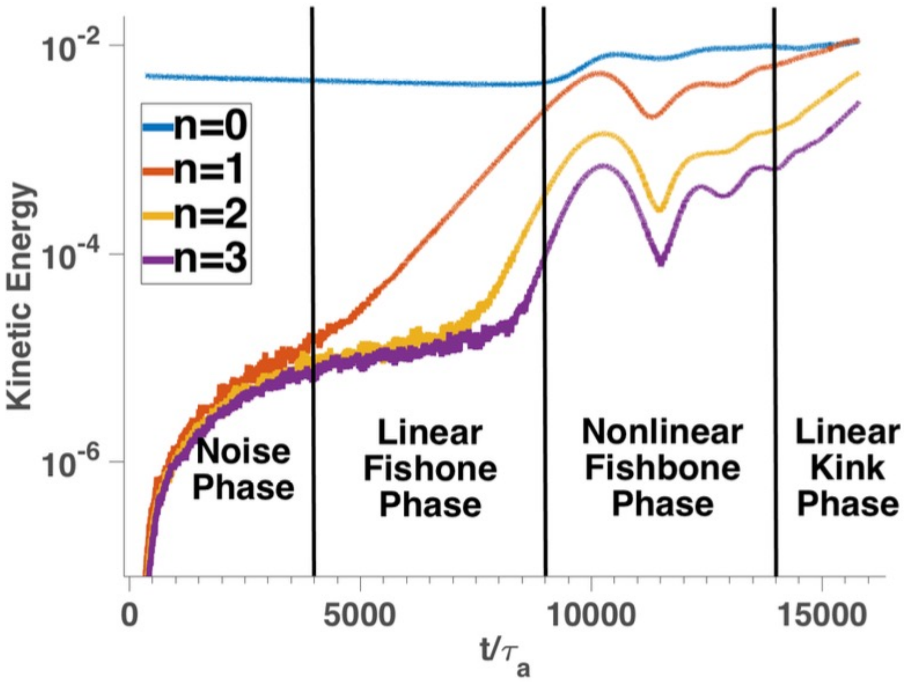
Outline:

- Status of XTOR-K before TSVV-02 and speed-up
- Applications: ITPA TAE and NL internal kink
- Generalization of fluid equations
- Ongoing work and perspectives

Status after PhD Brochard (2019) (1/2)

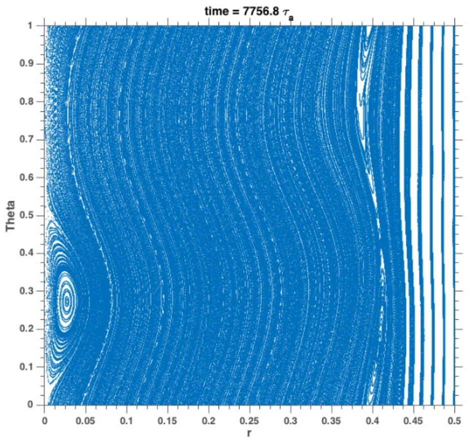


Alpha fishbone simulation with XTOR-K:

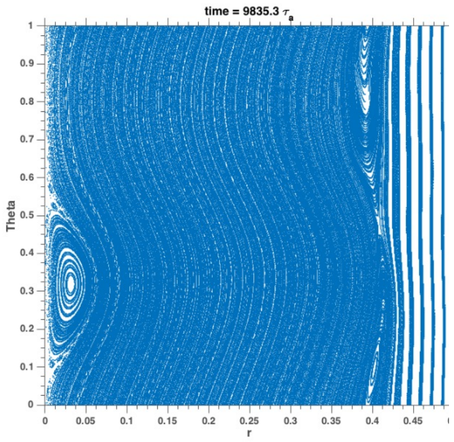
Evolution of K-energy of the n=0,1,2,3 modes

After linear growth and NL saturation of fishbone, growth of an underlying internal kink

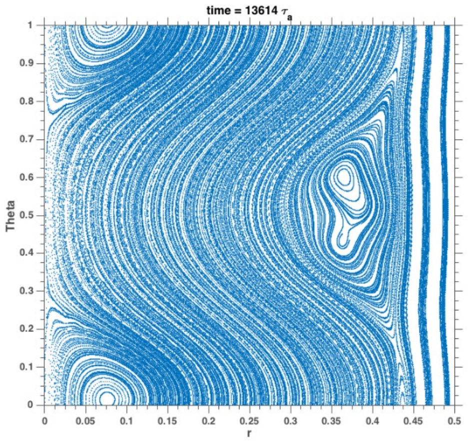
Status after PhD Brochard (2019) (2/2)



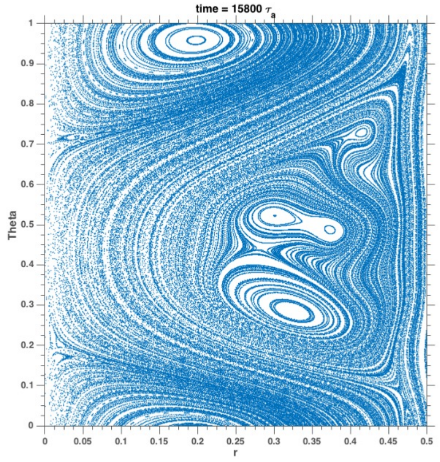
(a) $t = 7756.8\tau_A$



(b) $t = 9835.3\tau_A$



(c) $t = 13614\tau_A$



(d) $t = 15800\tau_A$

Poincaré sections of the magnetic field
a) and b) → alpha fishbone
c) and d) → internal kink

Problem :

Hybrid internal kink phase extremely slow:

- Typicaly 10 slices of 20h on with 512 MPI processes on Occigen
- Same limitations with hybrid simulations tearings

→ **Motivation to improve XTOR-K algorithm**

Numerical work on XTOR-k

- Step 1 (2021) : Introduction of new SPIKE algorithm. The fluid part is entirely domain-decomposed radially and in toroidal mode number or fluid sub-operators. Typical gain: factor 10. Fluid simulation of internal kink (linear phase + saturation): 15-30mn.

- Step 2 (First month of 2022): SPIKE adapted and validated in full XTOR-K (both domain cloning and domain decomposition PIC).

  -> Gain of an overall (hybrid) factor 2.5

- Particle sorting before moment deposition: DC another (hybrid) factor 2.

  DD No gain

- Computer speed-up between Occigen and Jean-Zay/ Irene Rome: factor 3.

<u>Résultat des courses:</u> about a factor 7 to 15 speedup between 2019 and now.

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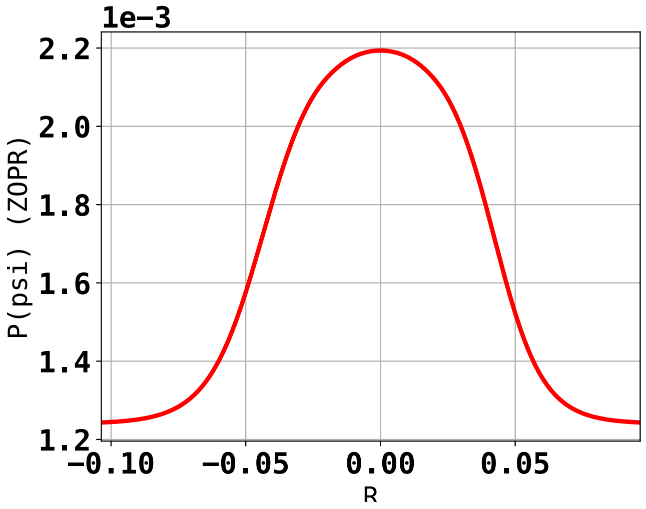
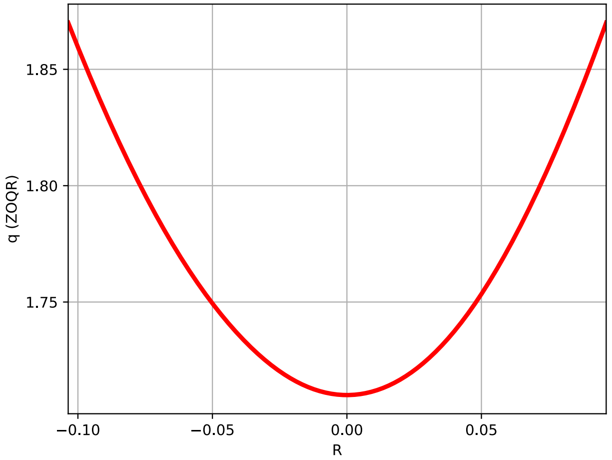
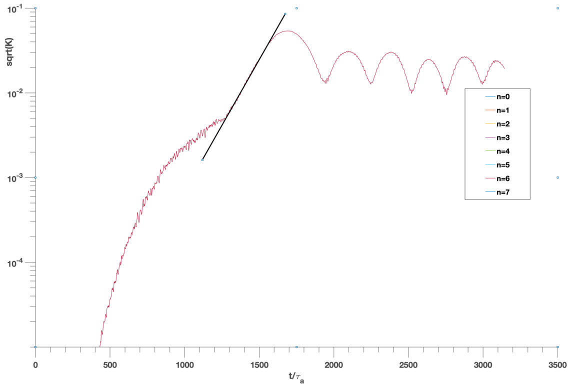
TAE simulations : Mishchenko TAE test case

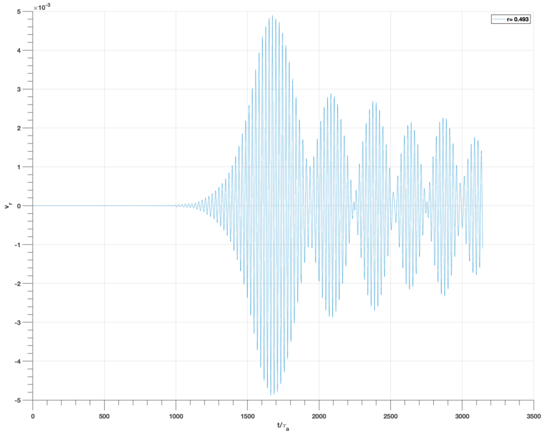


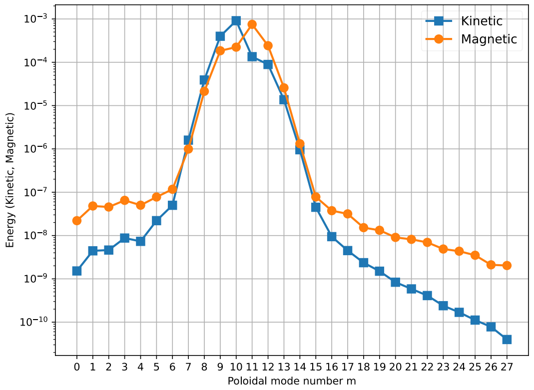


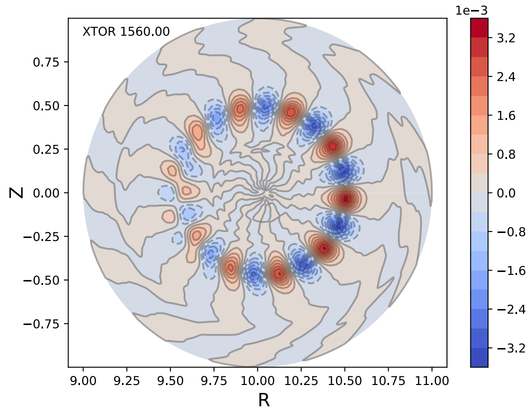
- Flat bulk hydrogen ion density ($n_i=n_e=2 \times 10^{19} m^{-3}$)
- Flat ion and electron temperature profiles (Ti=Te=1 KeV).
- Flat fast ion temperature (Tf=400keV)
- Fast ion density: ($n_k=0.75\ 10^{17}\ m^{-3}$ at q=1.75).
- Deuterium ions. Exp(tanh) shape
- CHEASE with fixed q profile
- B0=1T, R_0=10m, A=10

Applications: ITPA/Mishchenko TAE test case









n=6 TAE evolution:

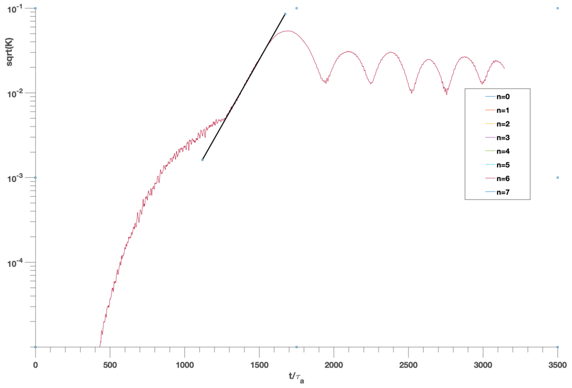
Gamma = 2.18 x 10^4 s^{-1}
Omega = 0.399 x 10^6 rad/s

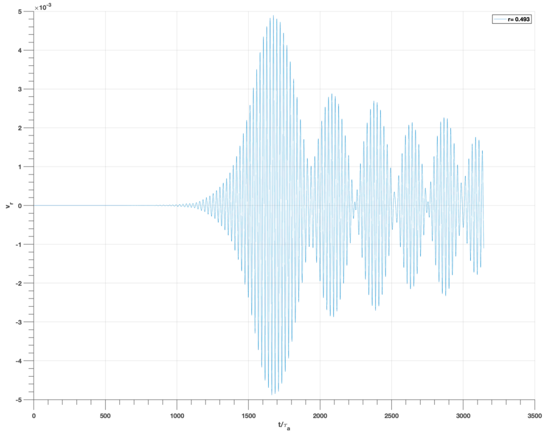
Compares well with
[Mishchenko 2009, Könies 2018]:

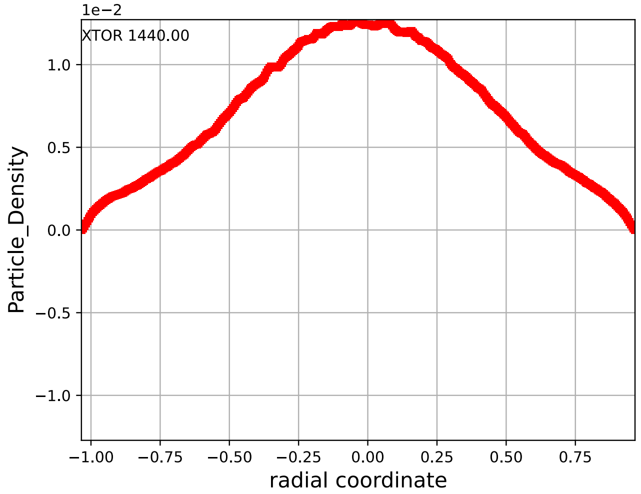
Gamma = 2.3 x 10^4 +/-10% s^{-1}
Omega = 0.42 x 10^6 rad/s

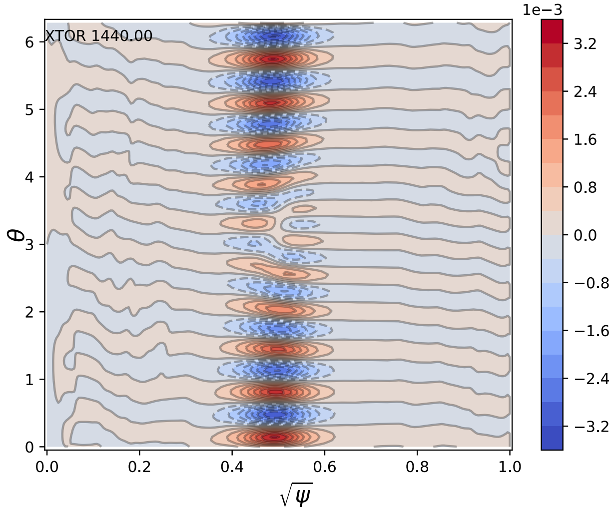
Omega ideal MHD eigenvalue code (CAS3D):
Omega = 0.401 x 10^6 rad/s

Applications: ITPA/Mishchenko TAE test case









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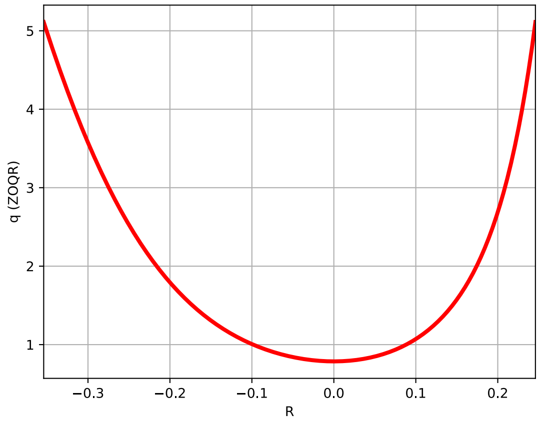
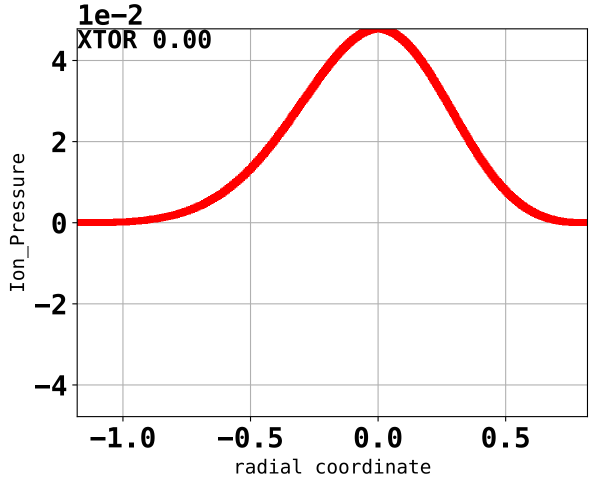
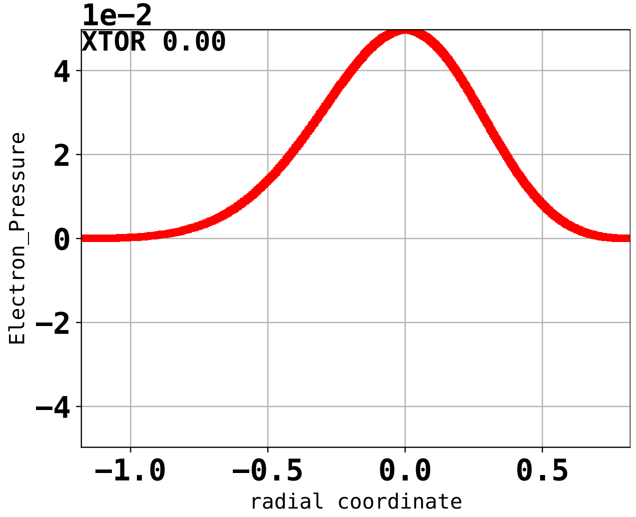
Loss of 25% of the kinetic Ions:

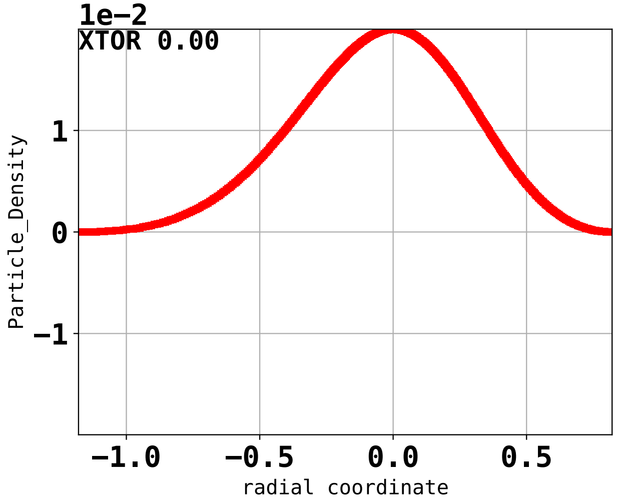
-> Would be good to compare with a vanishing K-density case at plasma edge

Applications: Internal kink simulations (MHD+alphas)







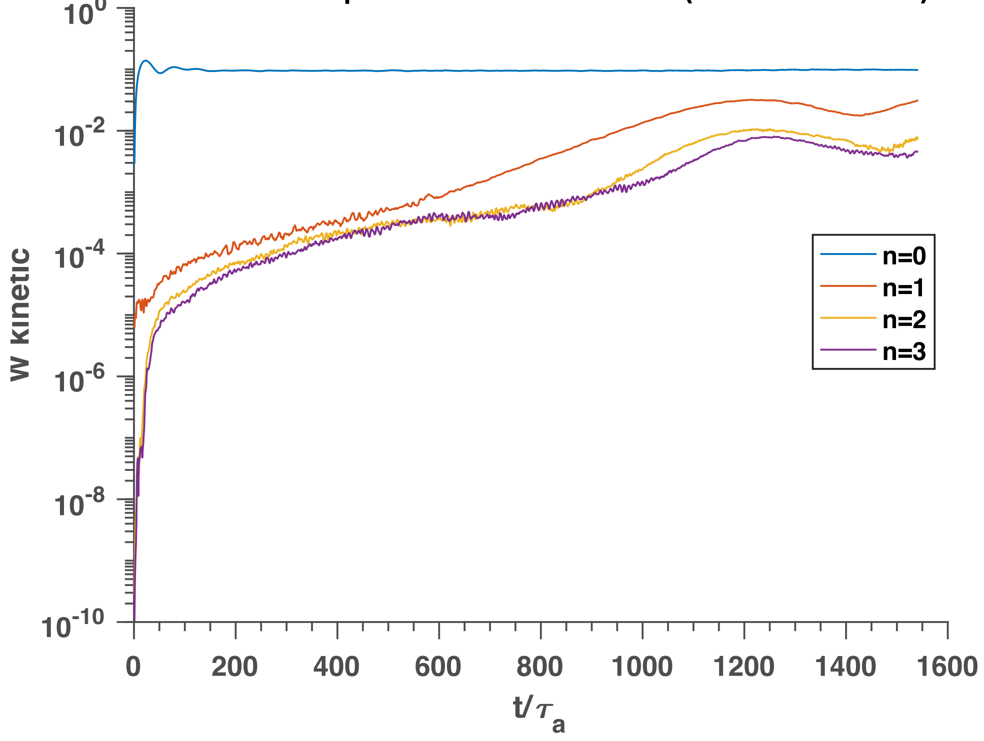


Ni0=ne0=2 10^19 m-3

Ti0=Te0=30KeV

Nf0=4.10^17 m-3

Alpha's of 3.5 MeV (Maxwellian)



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XTOR-K equations

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

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

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

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

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

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

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

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

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

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

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

$$\mathbf{v} = \mathbf{v}_{\mathbf{E}\times\mathbf{B}} + \mathbf{v}_{i,\parallel}$$

- Higher order corrections of fluid equations necessary for :
  - Sawtooth simulations (Halpern et al., Phys. Plasmas 18 (10) 102501)
  - Tearing simulations (all our work with P. Maget from CEA)

  → Particularly sensitive in weak kinetic drive situations

- »Gyroviscuous cancelation »:
  - XTOR-2F (JCP 229 (21) 8130) only $(\mathbf{v_i^*}.\nabla)\mathbf{v}_\perp$ kept.
  - Must be refined (Ramos, Phys. Plasmas 12 (5) 112301)

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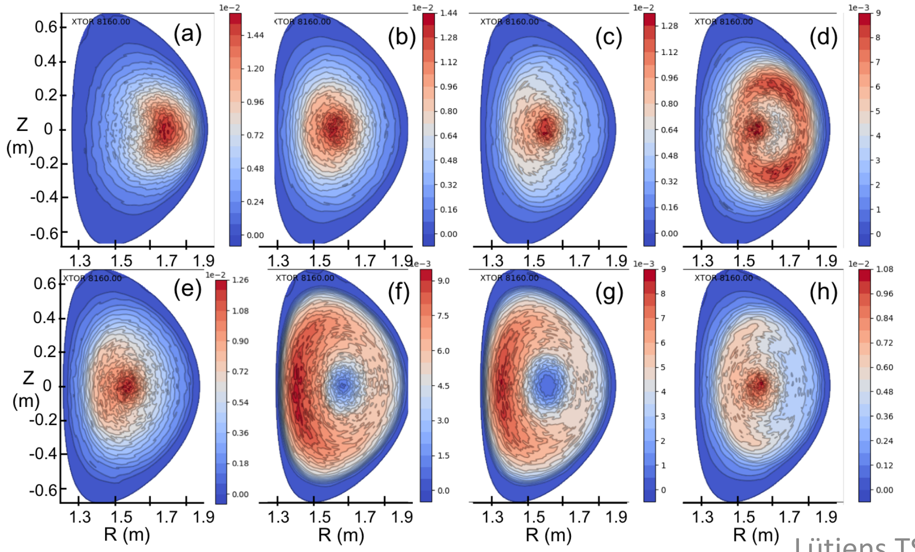
Ongoing work and perspectives

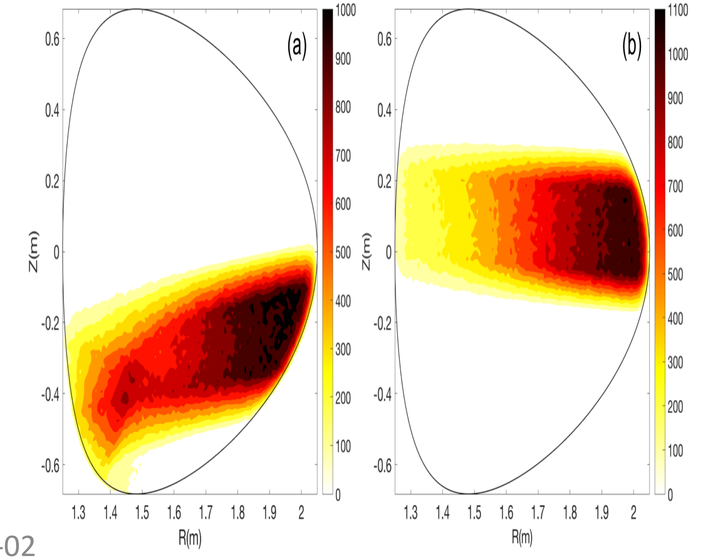
- Latest XTOR-K now contains both
  - Realistic model of Neutral Beam Injection, including modeling of the ionization process
  - Collisions between species and with the background plasma

- Possible to generate realistic PDFs of energetic particles
  - Mohamed Rekhis' PhD thesis: stability investigations with self-consistent energetic particles populations

- Work on more generalized fluid equations in progress



[Orain et al., ArXiv 2020]



Ongoing work and perspectives

- XTOR-K is now ready for long time simulations in the presence of kinetic ion populations :

  - Shaping effects on tearing/internal kink instabilities, interactions with fast particles or impurities

  - Sawtooth cycling simulations in the presence of fusion alphas will begin from now on

- Inclusion of an equilibrium plasma sepratrix in an advanced state