Recent progress on kinetic-MHD modeling of the interplay between fast particles and macroscopic modes in tokamak plasmas using XTOR-K

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Motivations: fast particles – MHD interaction

- ITER: fusion reactions induce fast particles α (3,5MeV)
  $\rightarrow$ confinement crucial for energy transfer
- Current tokamaks: fast particles induced by heating sources
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- Particles:
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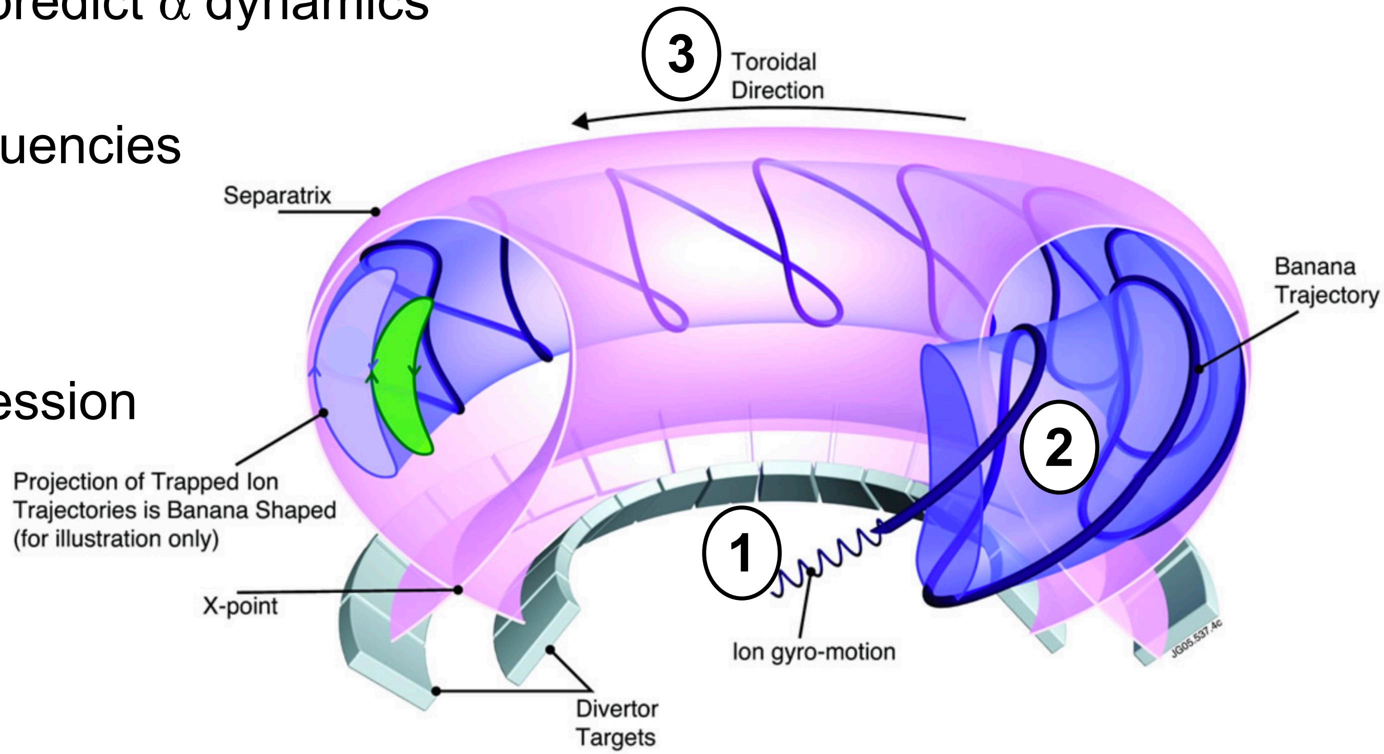
  $\rightarrow$ 1/ giration
  $\rightarrow$ 2/ bounce
  $\rightarrow$ 3/ toroidal precession



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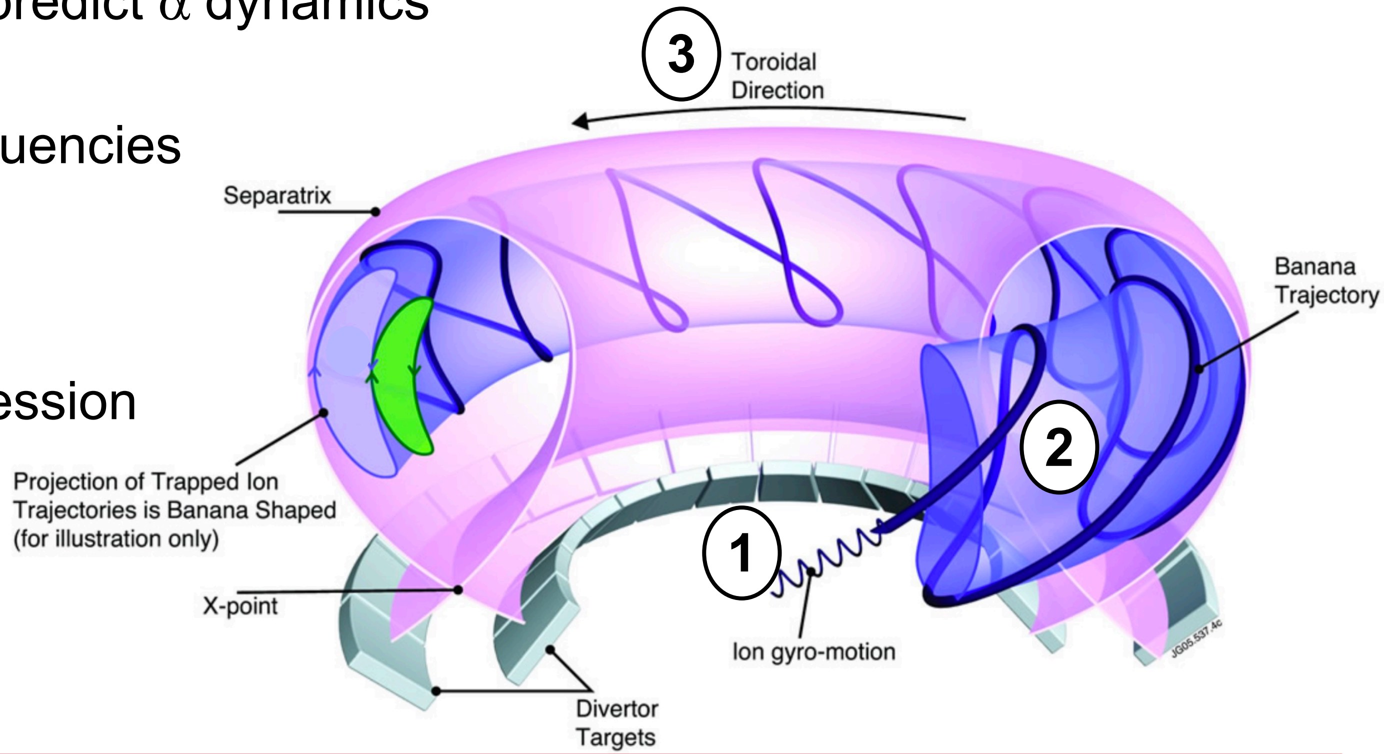
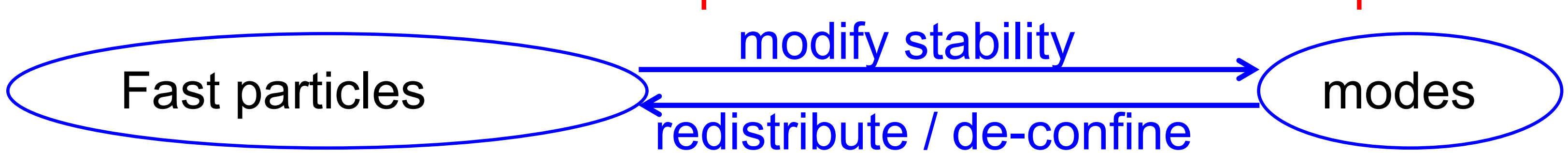
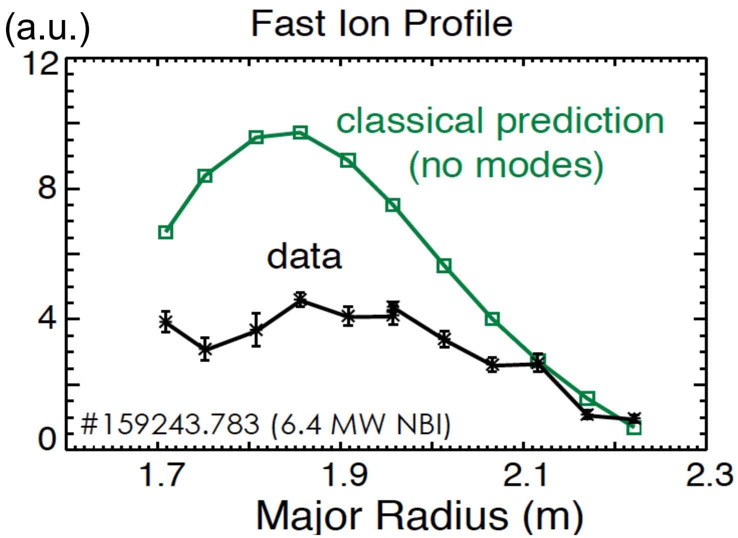


Resonance between these frequencies and MHD mode frequencies:



Motivations (2): key issues to be raised in modeling

- Fast particles can destabilize Alfvén Eigenmodes (AE):
  → Alfvén modes stable without fast particles.
  → Fast particles destabilize modes TAE / BAE / RSAE / UKAEA …
    → transport → degradation of confinement + losses damaging walls.



[DIII-D example, Heidbrink PRL2007]

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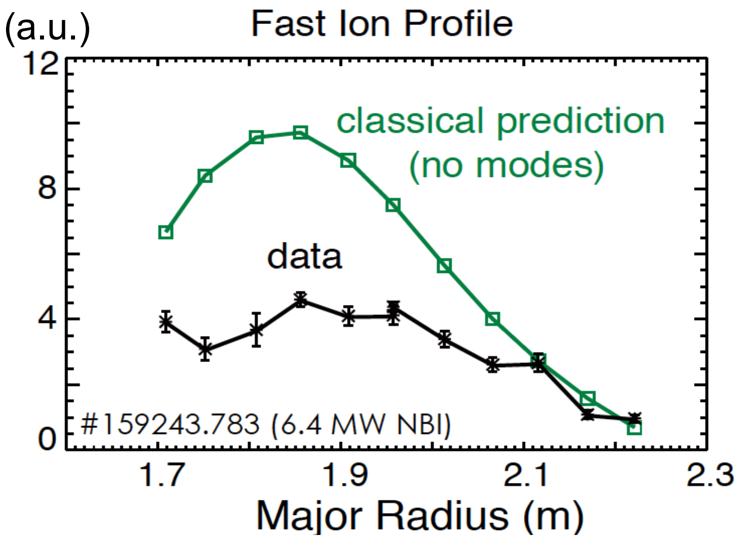

[DIII-D example, Heidbrink PRL2007]

- Fast particle interaction with sawteeth:
  → Fast particles can either stabilize sawteeth
    → monster sawteeth *[Chapman NF10]*
  → OR fast particles may destabilize fishbones
    → combined fishbones/sawteeth *[Nave NF91]* or no sawteeth *[Günter NF99]*

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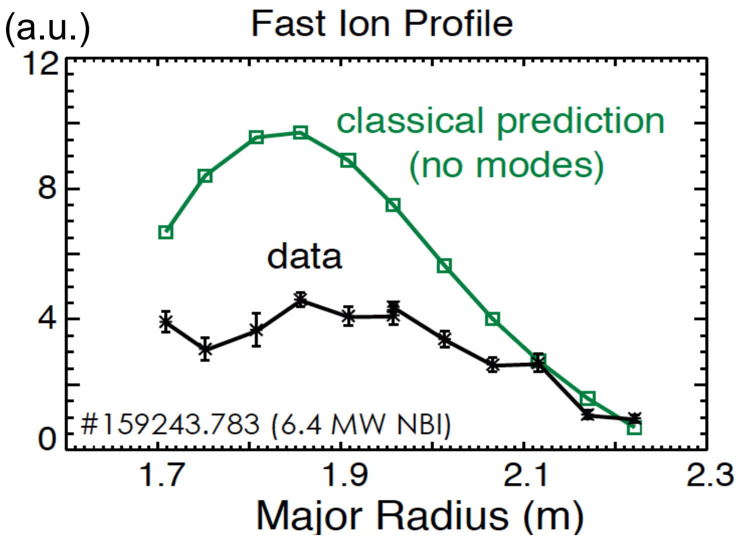

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Hybrid kinetic-MHD code XTOR-K

- Initially developed by H. Lütjens and J.F. Luciani *[Lütjens JCP10]*

XTOR-2F

Non-linear MHD solver

Time iteration of

(V,B,p,ρ)

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

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

$$\nabla \cdot \Pi$$

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

PIC Module

Full f, full orbit

Particle Pusher

(*r*,*v*)

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

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

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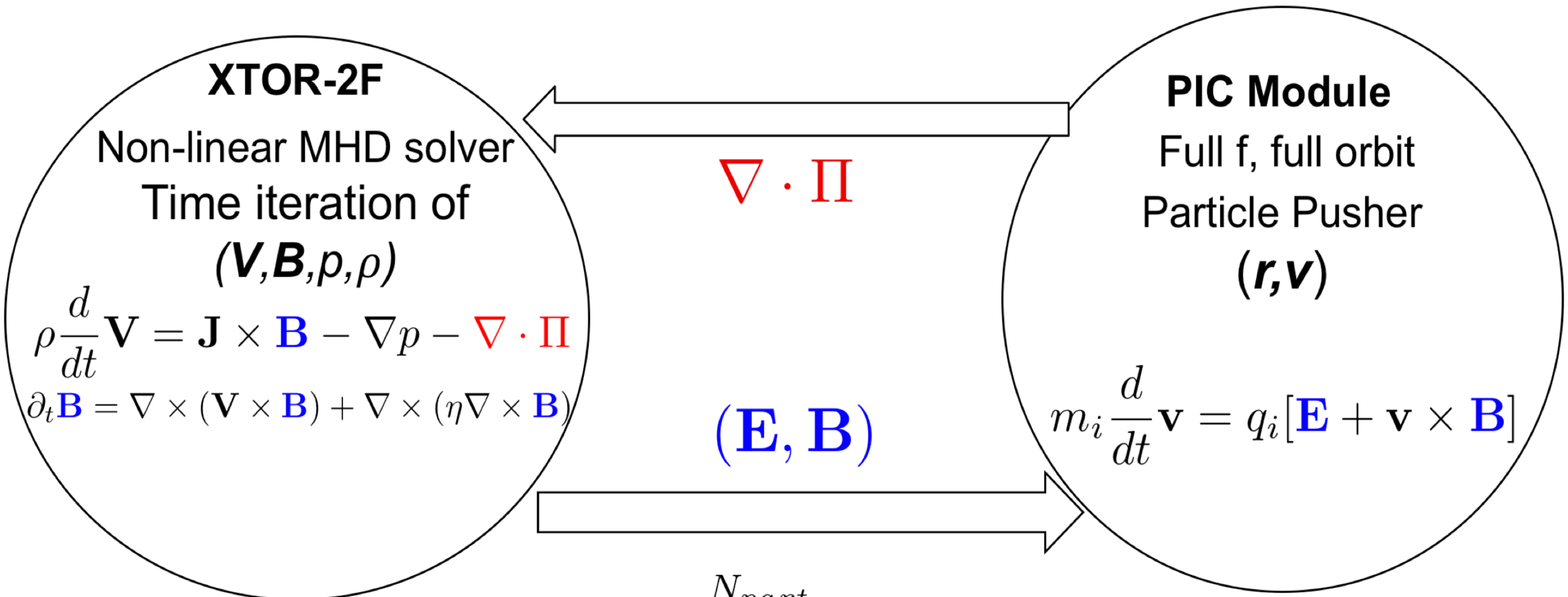

$$\Pi(\mathbf{r},t) = m_i\sum_{n=1}^{N_{part}}\mathbf{v}_n\mathbf{v}_n\delta(\mathbf{r}-\mathbf{r}_n(t))$$

- Input for the code:
  → Equilibrium bulk profiles from CHEASE code *[Lütjens CPC96]*
  → Maxwellian or slowing-down kinetic distribution function

- Boundary conditions: plasma described inside separatrix: OK for core physics

Outline

- Fishbone/sawtooth dynamics using slowing-down fast-particle distribution *[Brochard PhD thesis 2019]*

- MHD interaction with NBI-induced fast particles

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  - → Tool for preliminary studies: linear fishbone model
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Linear model for fishbone instability *[G. Brochard]*

- Considers energy principle in kinetic-MHD form:

Kinetic energy of instability $\delta I = \delta W_{MHD} + \delta W_K$

MHD potential energy

Fast particle potential energy

*[Chen PRL83,
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$$\delta W_K = -\frac{1}{2}\int d^3\mathbf{x}d^3\mathbf{v}\ \boldsymbol{\xi}^* \cdot \nabla \cdot (\mathbf{v} \otimes \mathbf{v}\tilde{f}_h)$$

MHD displacement

Perturbed fast particle distrib. function

→ Solves complex kinetic-MHD dispersion relation for fishbone instability

[Brochard JPCS 2018]

➢ Model hypotheses:

→ Thin orbit width

→ $\beta_{fast} << \beta_{total}$

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Goal: quick linear stability analyses for internal kink and fishbone
→ pave the way for long non-linear simulations with XTOR-K

2 branches of instabilities on q=1 depending on fast particle fraction: kink or fishbone modes

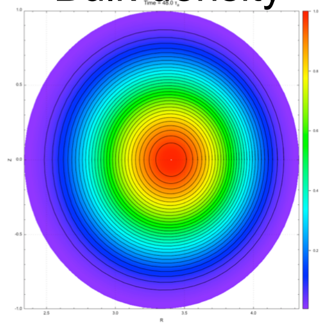
- Circular ITER-like test case :

  → Isotropic slowing-down distrib., peak energy of 1MeV

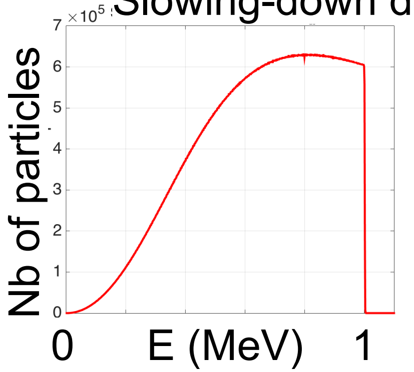
  → peaked fast particle density:

$$n_\alpha(r) = n_{\alpha,0}(1 - r^2)^6$$

Bulk density



Slowing-down distrib.



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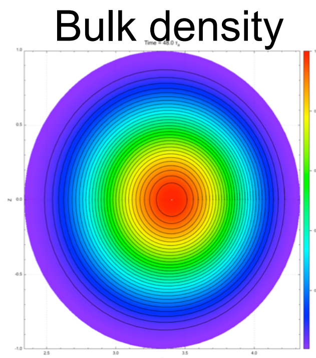
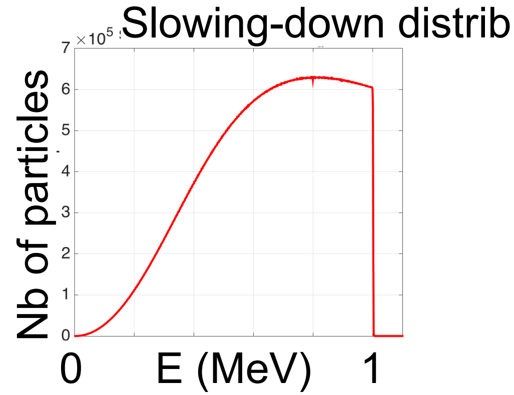
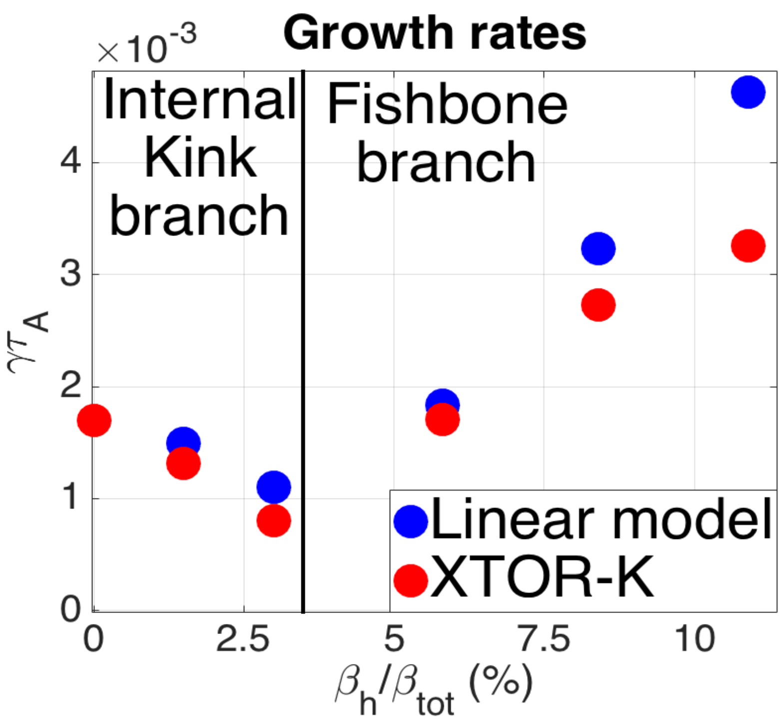
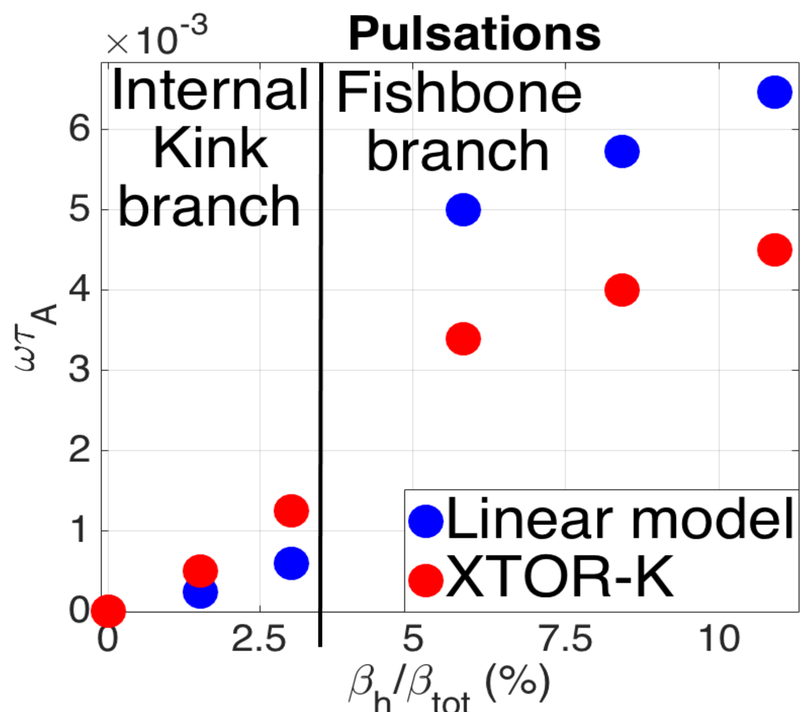




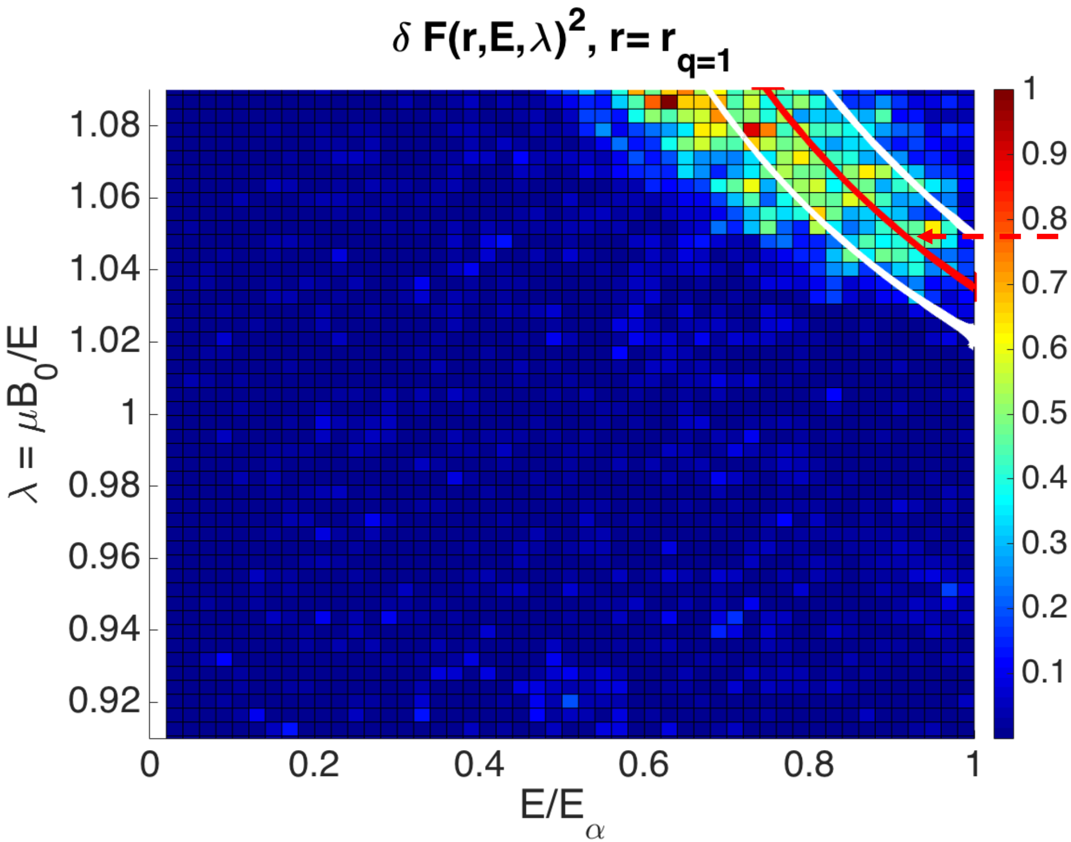




- **Qualitative agreement on linear stability between linear model and XTOR-K**

Resonant regions in phase-space

- Passing VS trapped particles characterized by pitch-angle $\lambda \propto \mu$
  $\rightarrow$ here trapped: $\lambda > 0.87$



Resonant zone in linear model

- Zones of precessionnal resonance similar in linear model and XTOR-K

- Fishbone/sawtooth dynamics using slowing-down fast-particle distribution *[Brochard PhD thesis 2019]*
  - → Tool for preliminary studies: linear fishbone model
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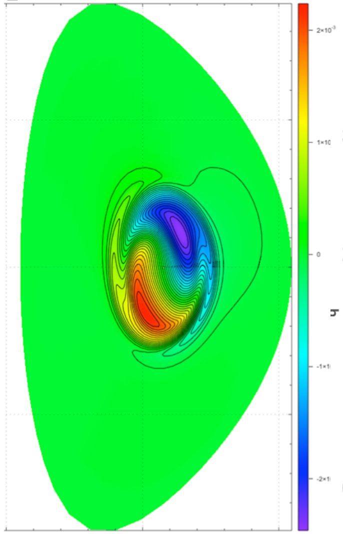
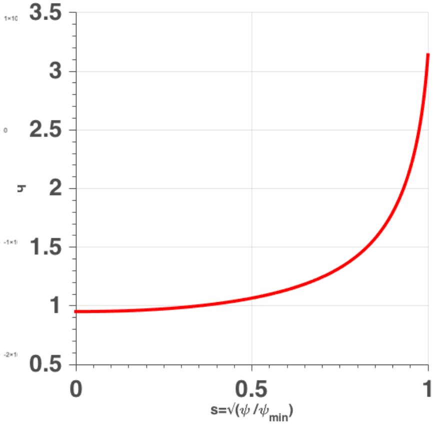
ITER 15MA scenario: fishbone may be unstable below expected fast particle fraction

- Realistic ITER 15MA scenario
  - → $n_{i0} = 10^{20}\ m^{-3}$
  - → $T_{i0} = T_{e0} = 23$ keV

  Profiles as in integrated modeling codes
  - → slowing-down distrib of α (birth @ 3,5MeV)
  - **→ Goal 🥅: check fishbone stability in ITER + study dynamics**



q profile:
q=1 @ s=0.4



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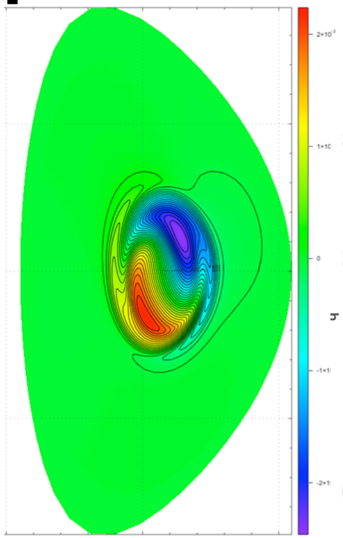

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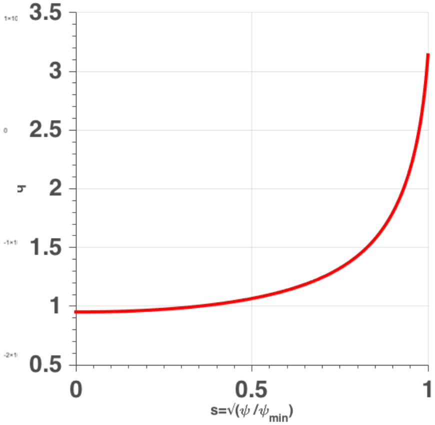
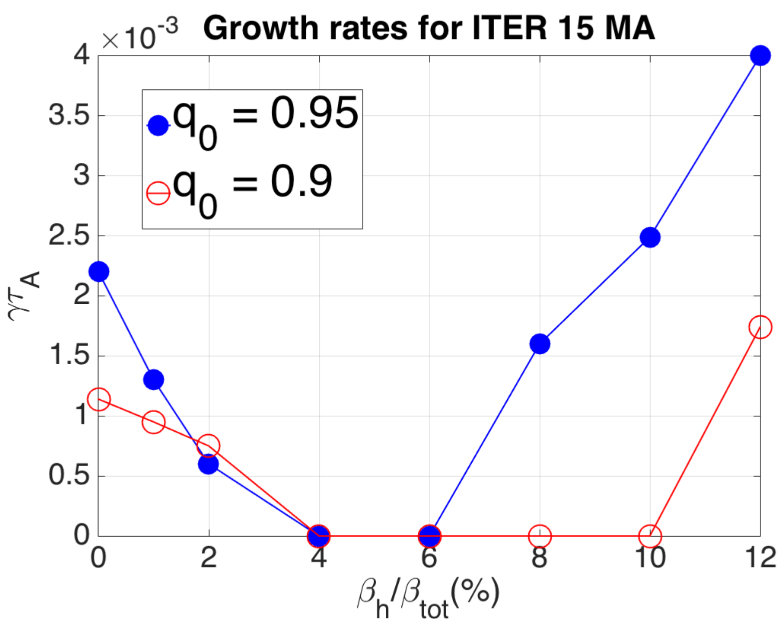
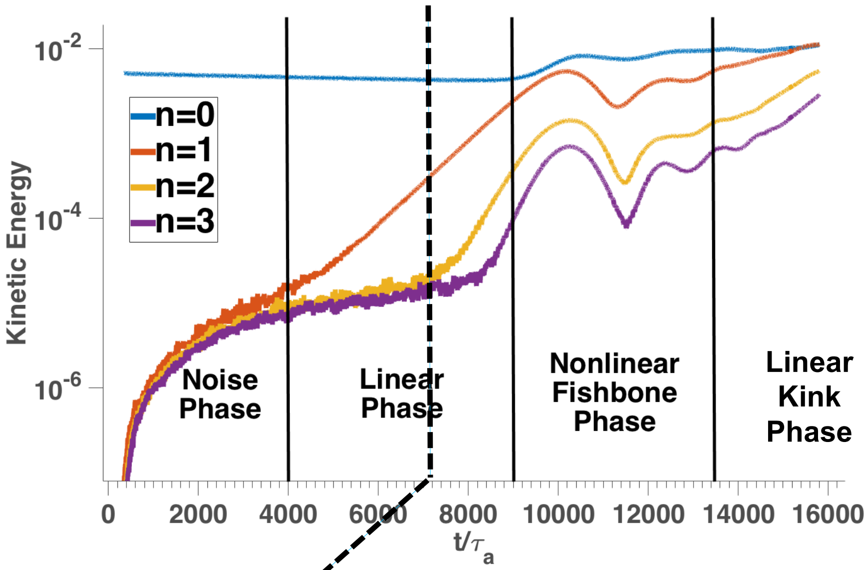




- For $q_0 = 0.95 - 0.9$, threshold for fishbone instability: p_{fast} / p_{tot} = 6-10%

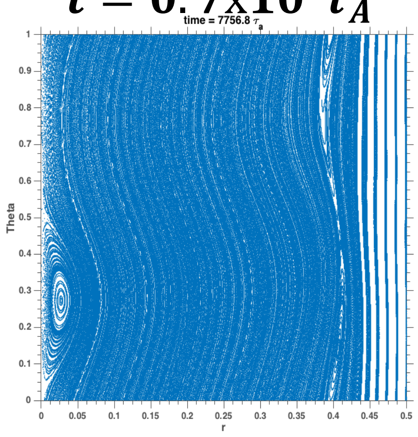
- ITER physics basis p_{fast} / p_{tot} > 15% $\rightarrow$ fishbone-unstable!

Non-linear modeling of fishbone followed by internal kink



Fishbone begins

$t = 0.7\text{x}10^4\tau_A$



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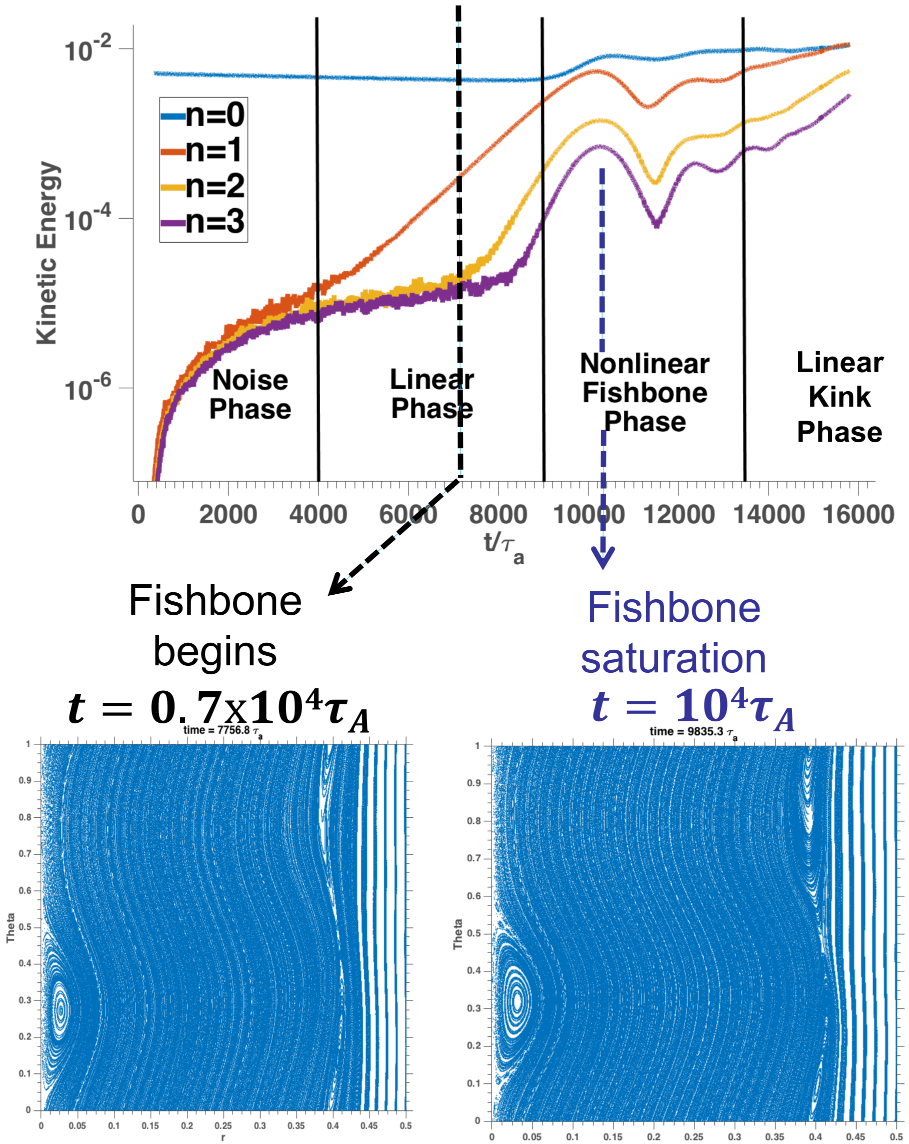

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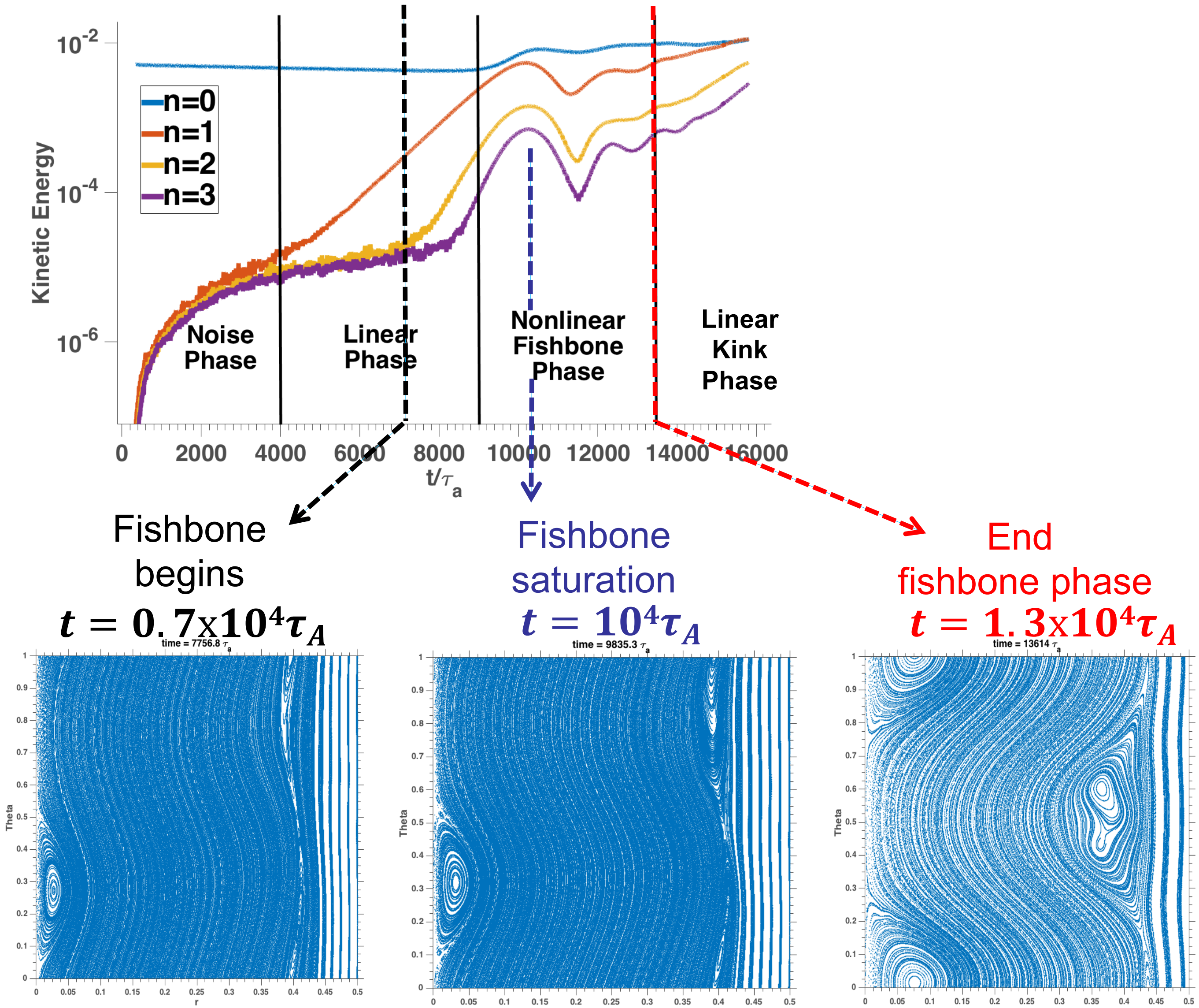

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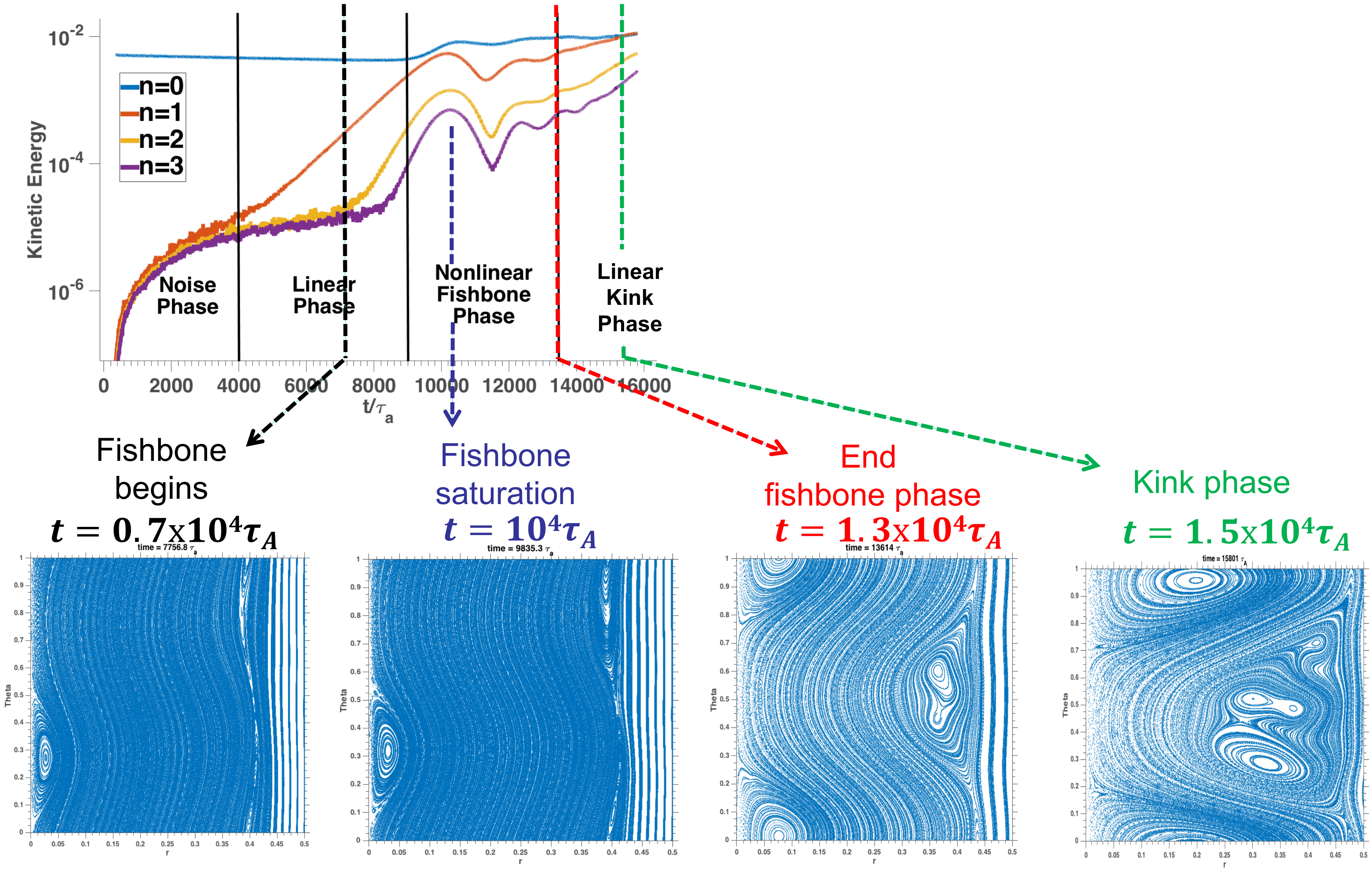

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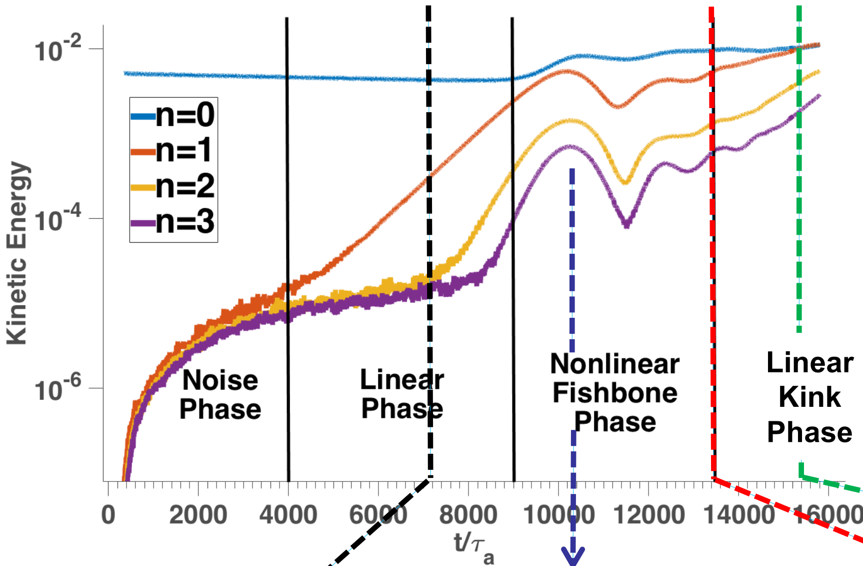

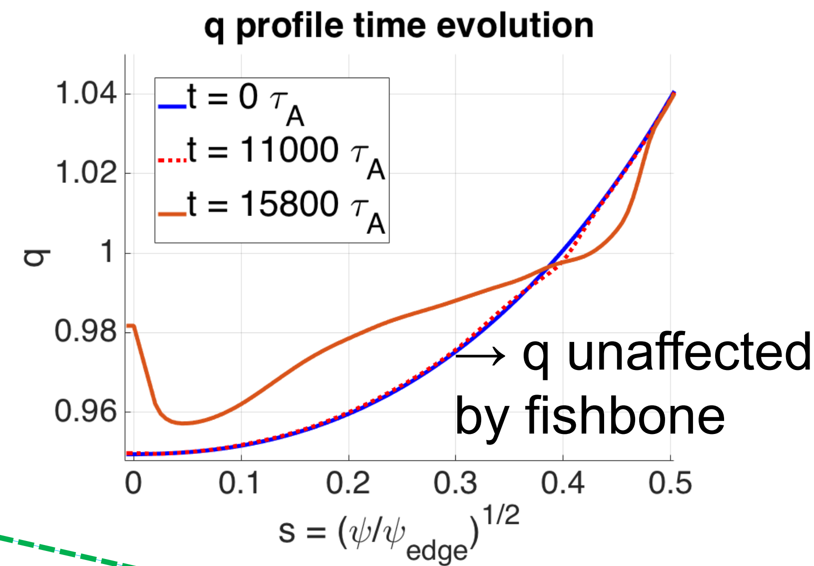

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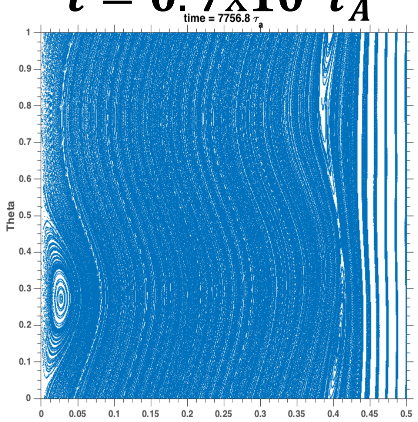
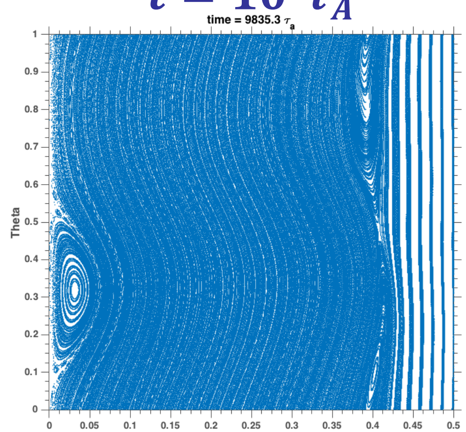


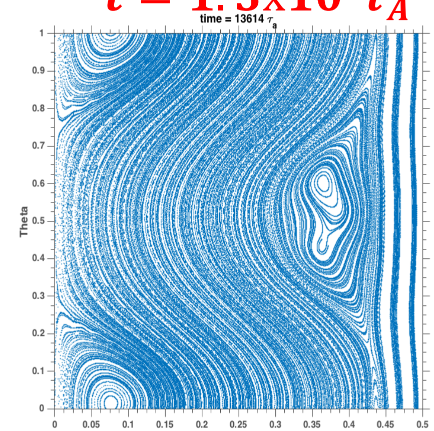
Fishbone saturation

$t = 10^4\tau_A$



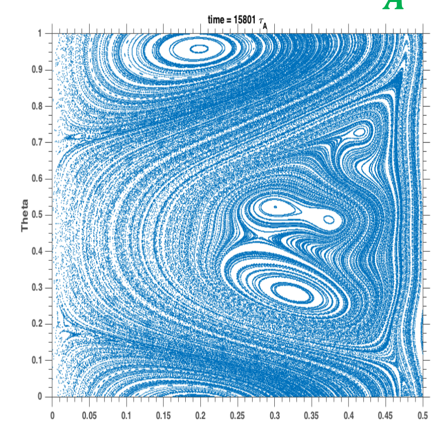
End fishbone phase

$t = 1.3\text{x}10^4\tau_A$



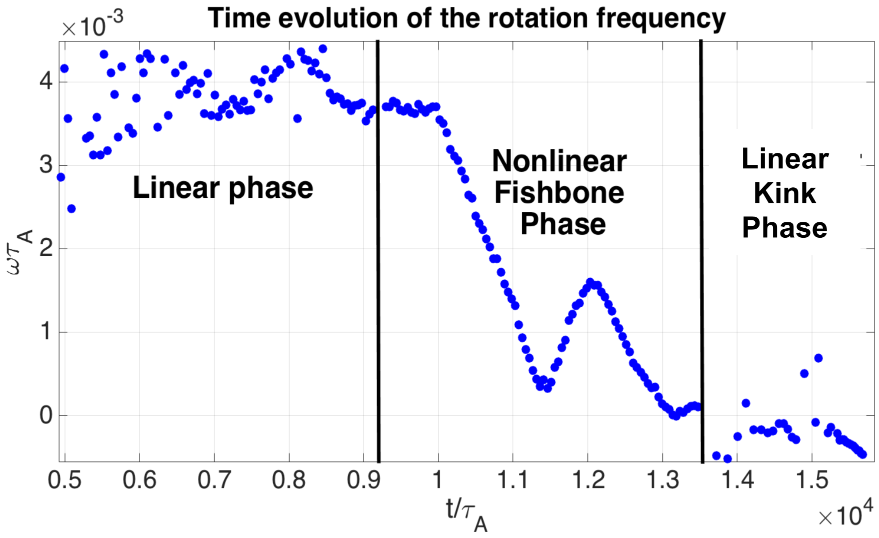
Kink phase

$t = 1.5\text{x}10^4\tau_A$



Resonant particle transport induced by fishbones

➢ Chirping during fishbone oscillations…



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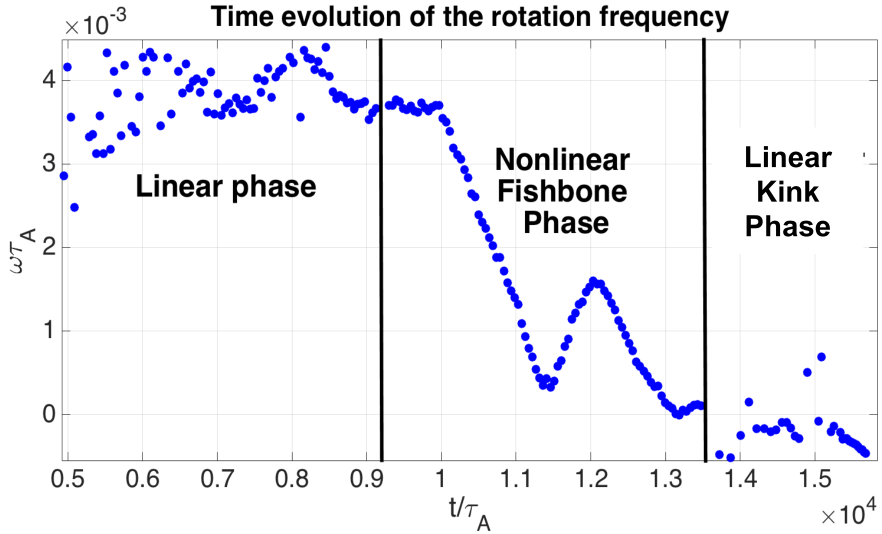
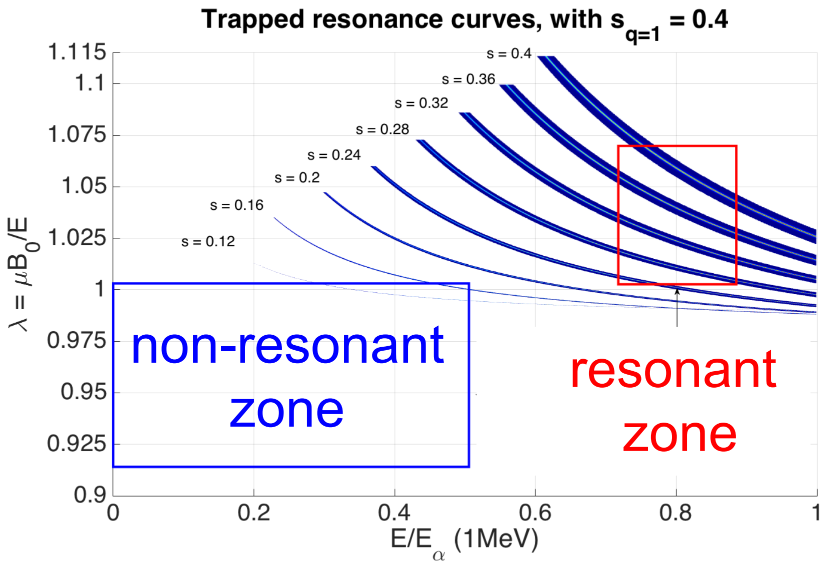
➢ Chirping during fishbone oscillations… associated with flattening of resonant fast particle profile



Mode frequency $\omega \propto \nabla n_\alpha$



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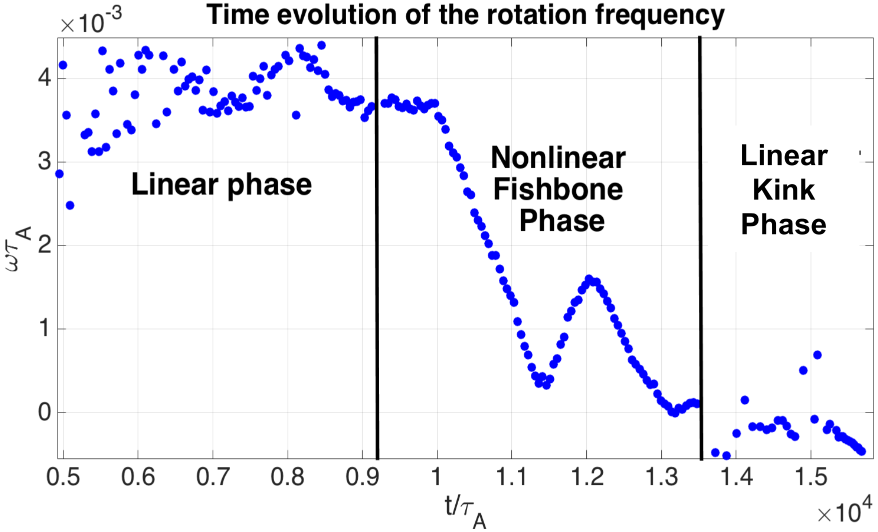

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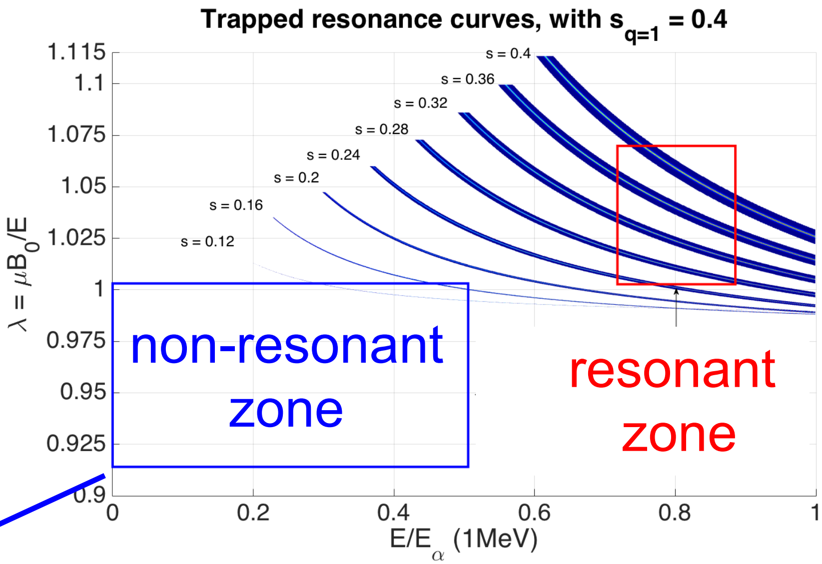

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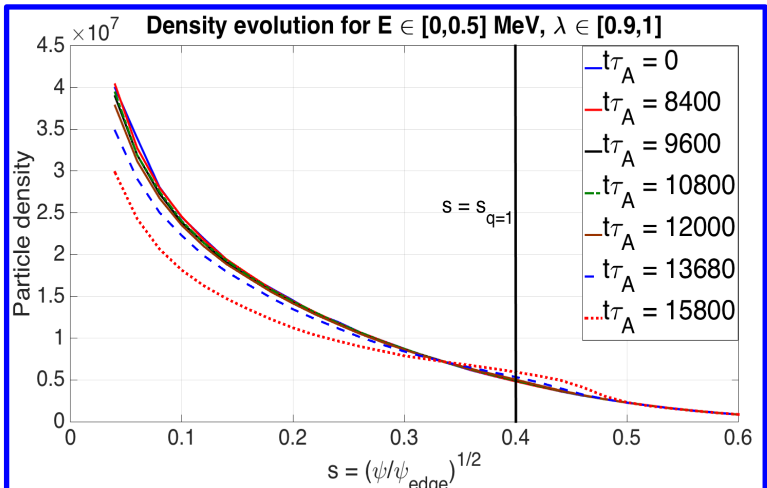

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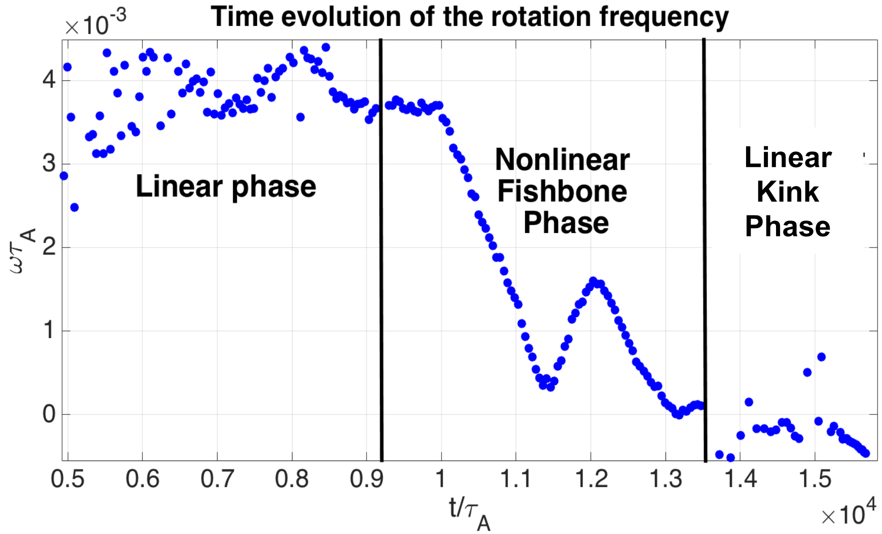

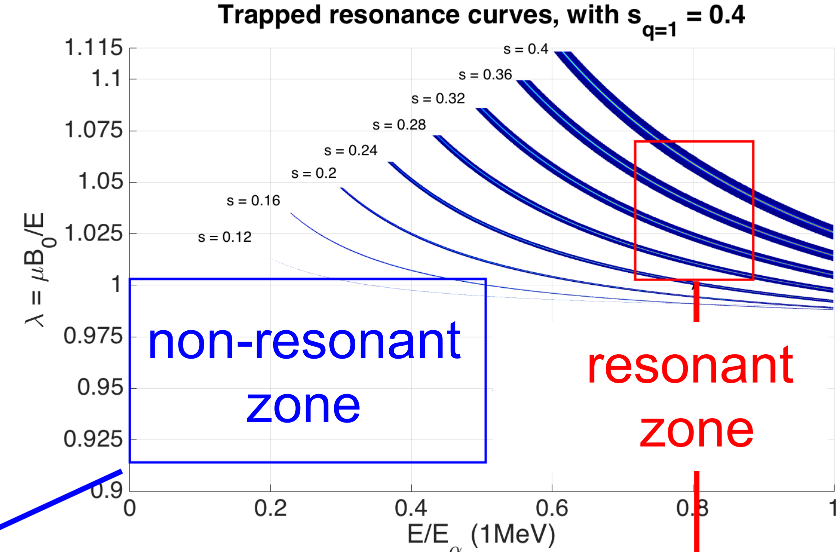

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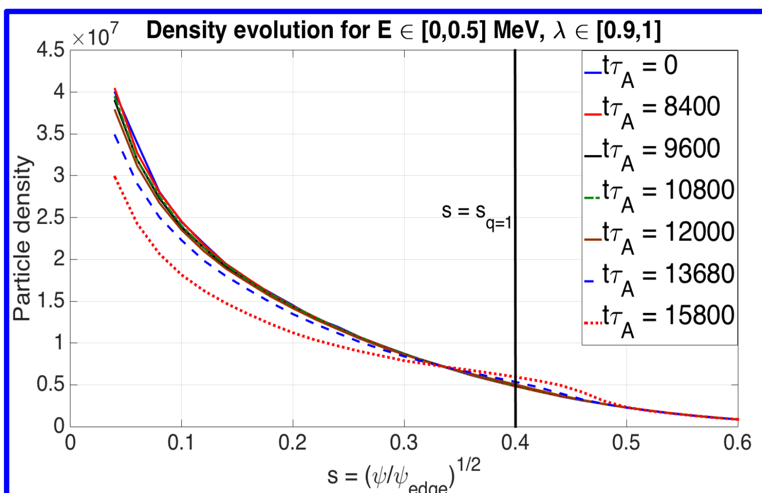

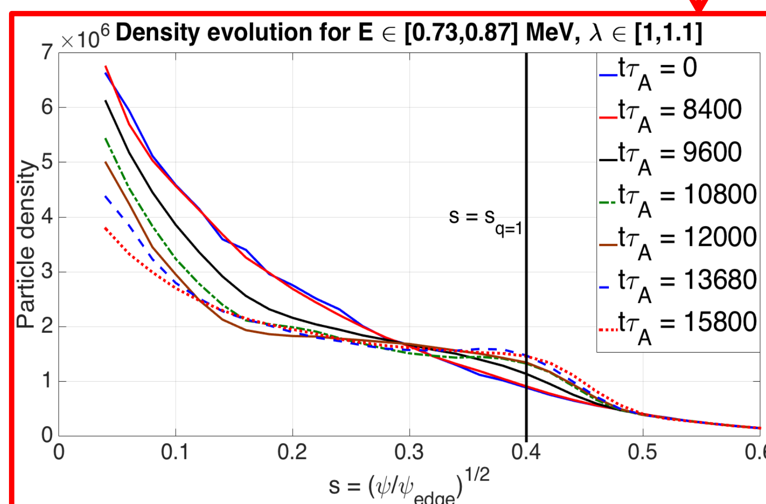

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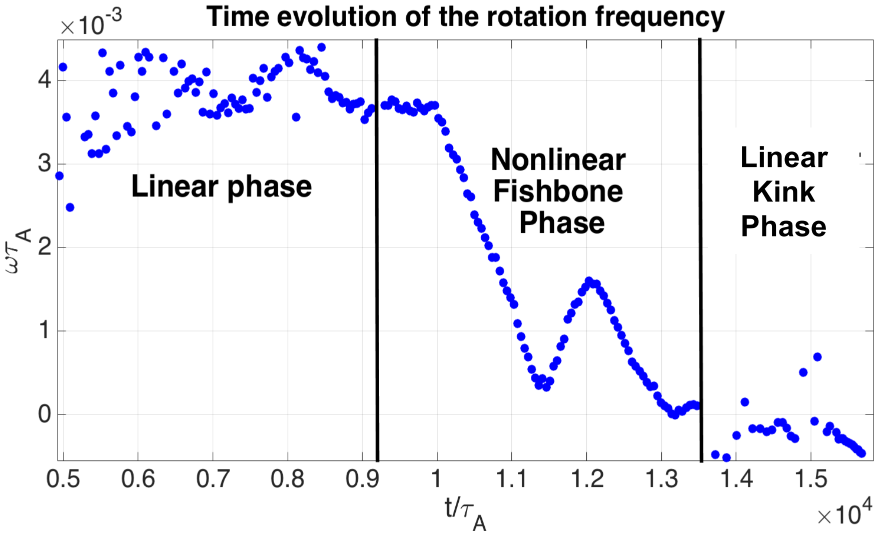

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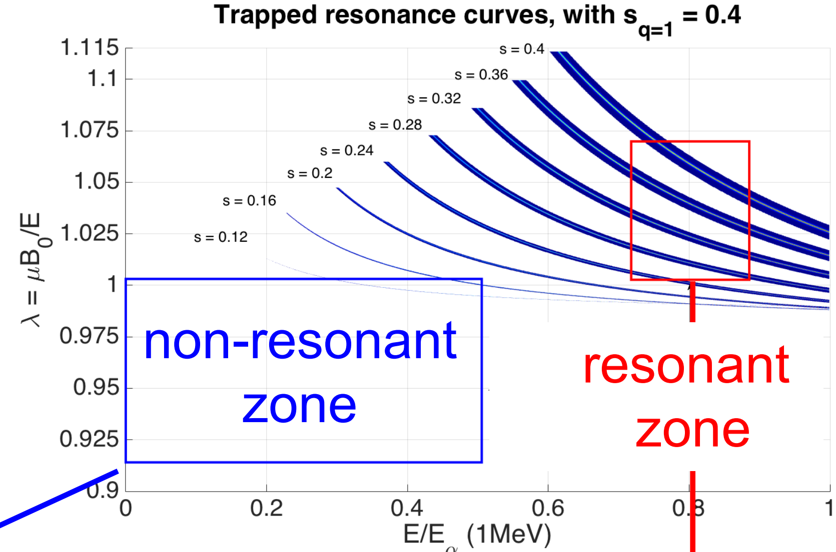

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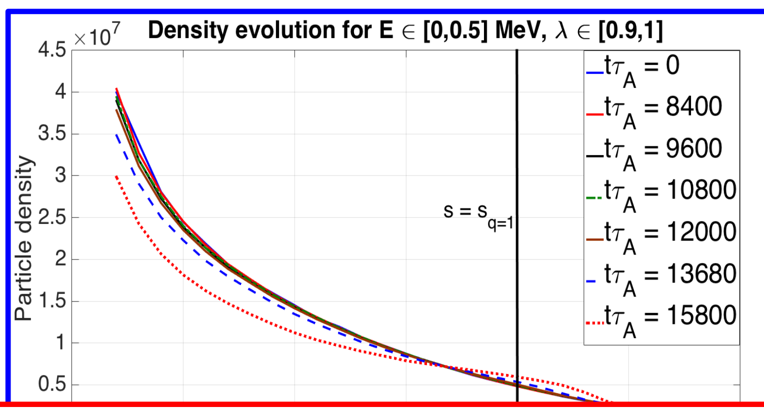

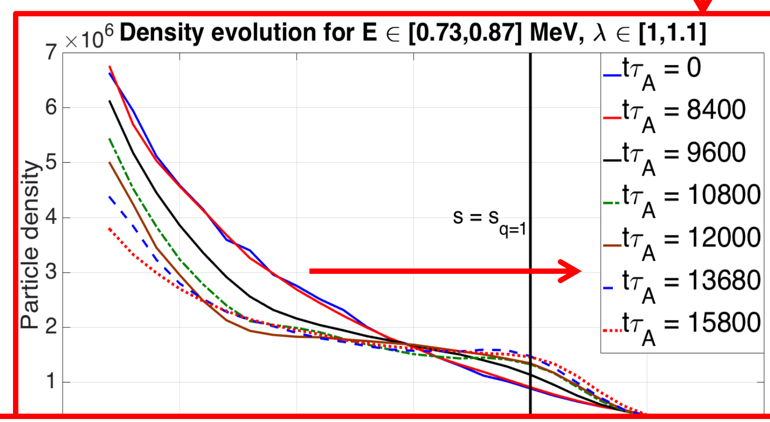

6% of fast particles inside q=1 move outward due to fishbone

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  - → Tool for preliminary studies: linear fishbone model
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- MHD interaction with NBI-induced fast particles
  - → New features in XTOR-K: collisions and NBI
  - → Ongoing work towards fishbone induced by NBI

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Feat #1: Collisions in XTOR-K *[Timothée Nicolas]*

- XTOR-K contains **kinetic** markers and **fluid** populations

Fluid: *T*, *v* maxwellian

$$\rightarrow \quad \mathcal{C}[f,f] = -\frac{\partial}{\partial \boldsymbol{v}} \cdot \left(\mathbf{F} f - \frac{1}{2} \frac{\partial}{\partial \boldsymbol{v}} \cdot (\bar{\mathbf{D}} f) \right)$$

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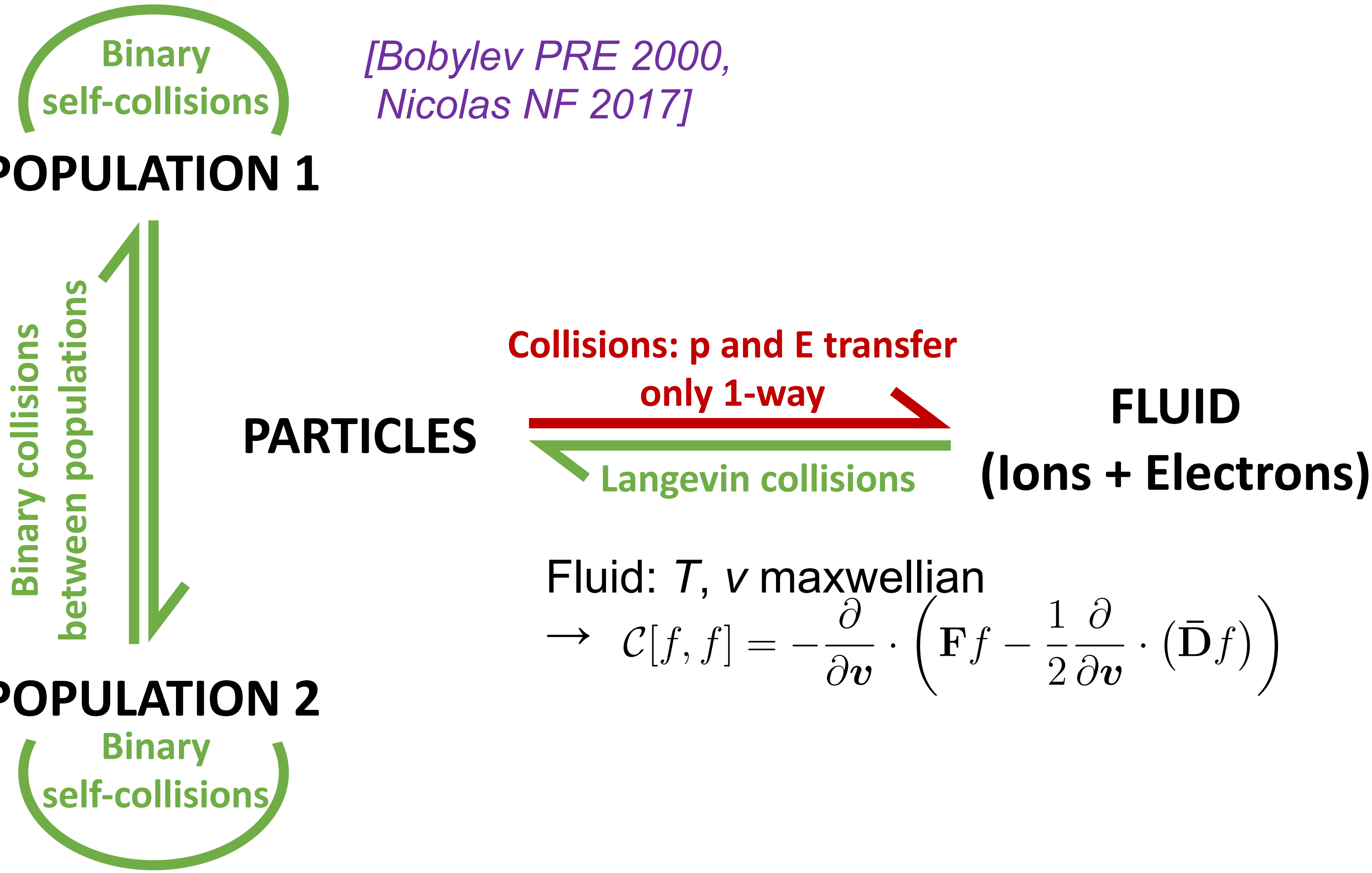
- XTOR-K contains **kinetic** markers and **fluid** populations

[Bobylev PRE 2000, Nicolas NF 2017]

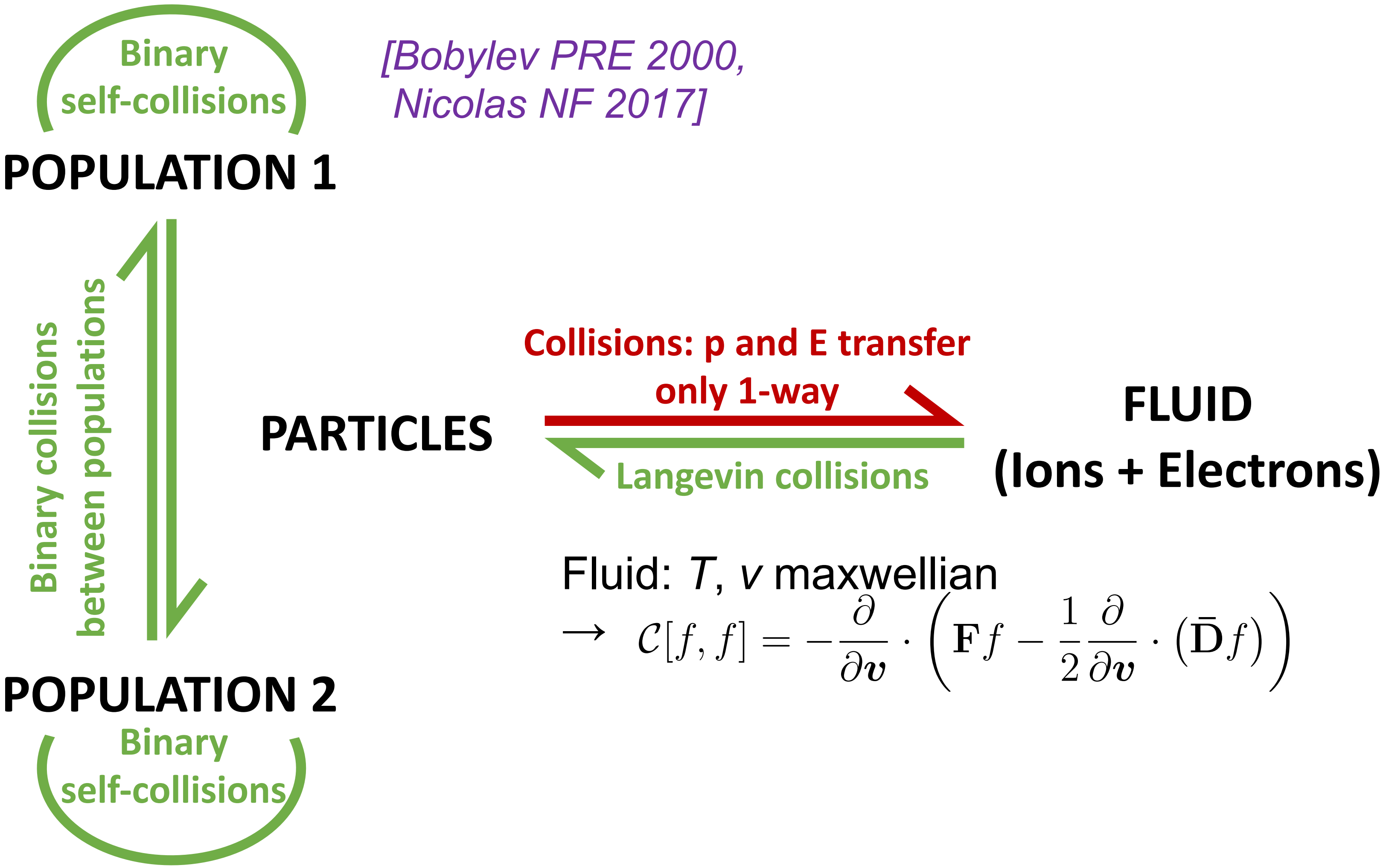


Fluid: *T*, *v* maxwellian

$$\rightarrow \quad \mathcal{C}[f,f] = -\frac{\partial}{\partial \boldsymbol{v}} \cdot \left(\mathbf{F} f - \frac{1}{2} \frac{\partial}{\partial \boldsymbol{v}} \cdot (\bar{\mathbf{D}} f) \right)$$

Feat #1: Collisions in XTOR-K *[Timothée Nicolas]*

- XTOR-K contains **kinetic** markers and **fluid** populations



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Fluid: T, v maxwellian

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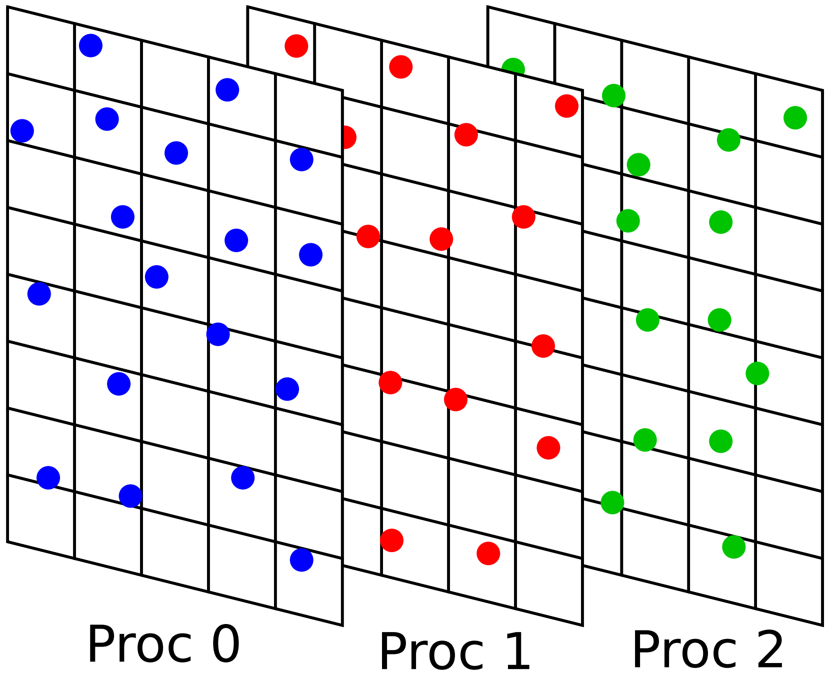
- Validated with typical relaxation tests.

Domain decomposition needed for collisions

Domain Cloning:
Binary collisions impossible



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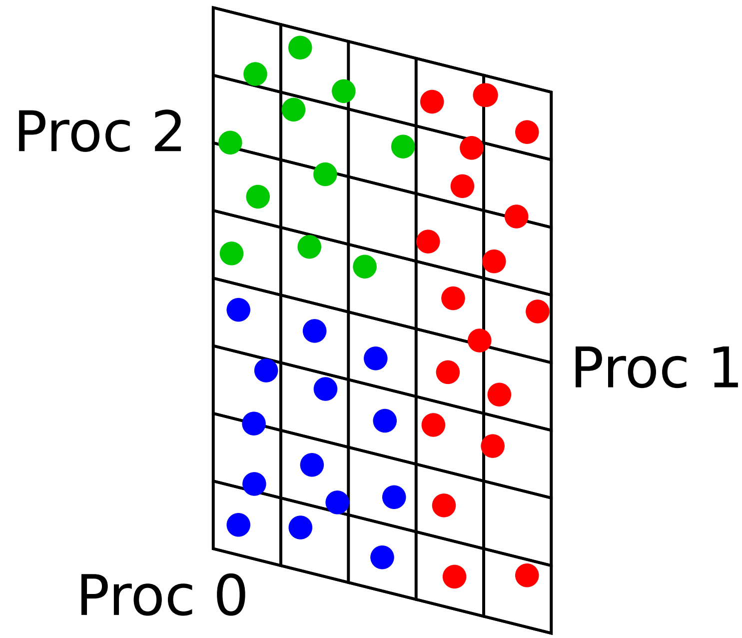


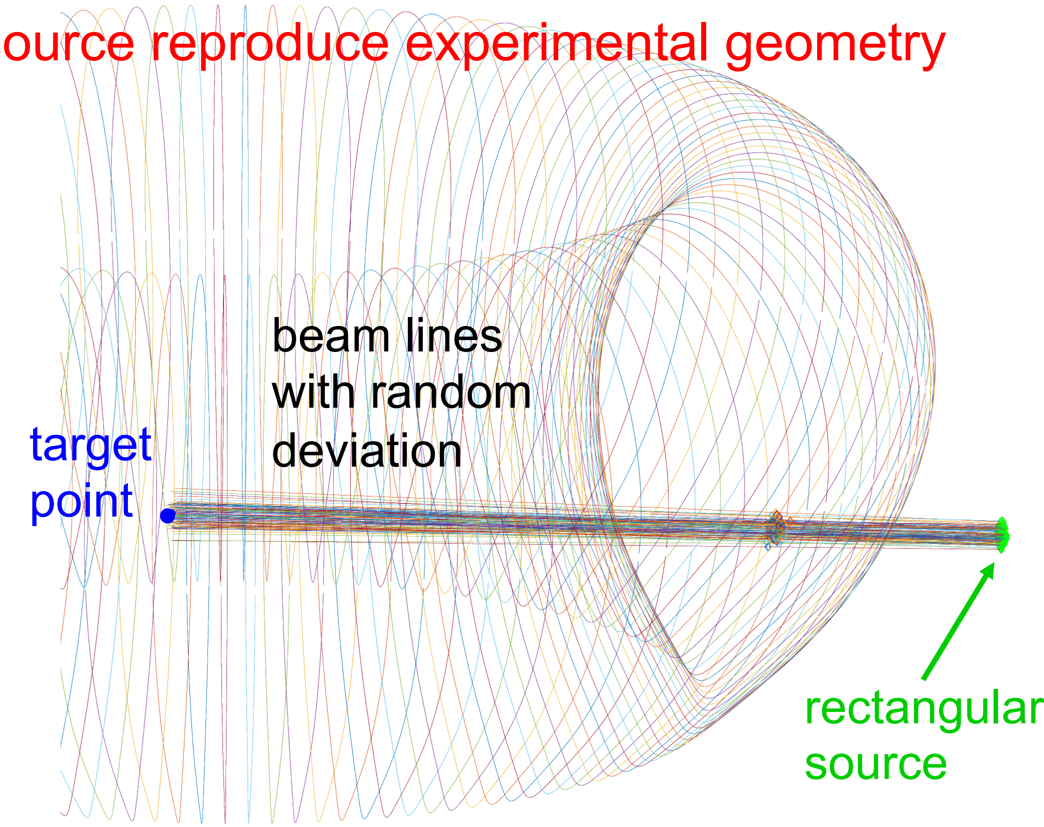
➢ Domain decomposition also improves performances: speed-up = 1.7 times

Feat #2: Realistic fast ion source induced by Neutral Beam Injection (NBI) *[F. Orain]*

→ Kinetic module: neutral particle source reproduce experimental geometry

→ Injection rate depends on beam power and energy

→ Neutral particles follow a line towards a target point with random deviation



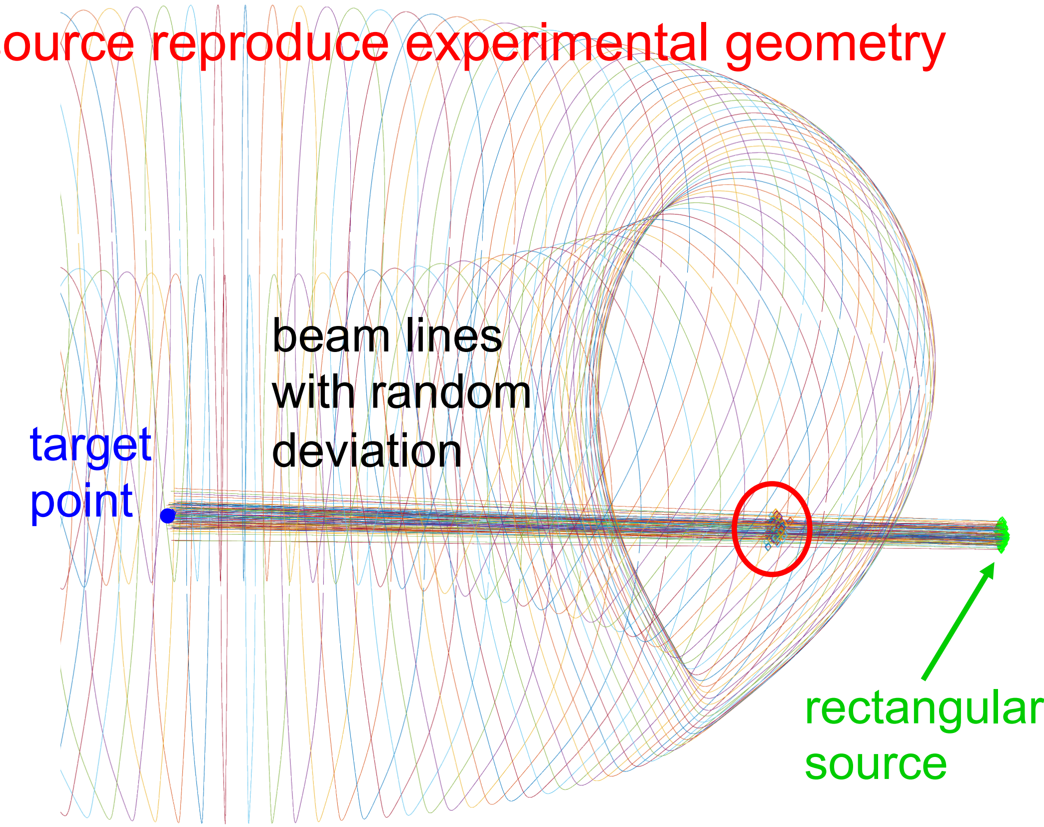
Feat #2: Realistic fast ion source induced by Neutral Beam Injection (NBI) *[F. Orain]*

→ Kinetic module: neutral particle source reproduce experimental geometry

→ Injection rate depends on beam power and energy

→ Neutral particles follow a line towards a target point with random deviation

→ Along this line, cumulative ionization probability is calculated :



$$1 - P(l) = \big(1 - P(l - \Delta l)\big)\exp(-n_e \sigma \Delta l)$$

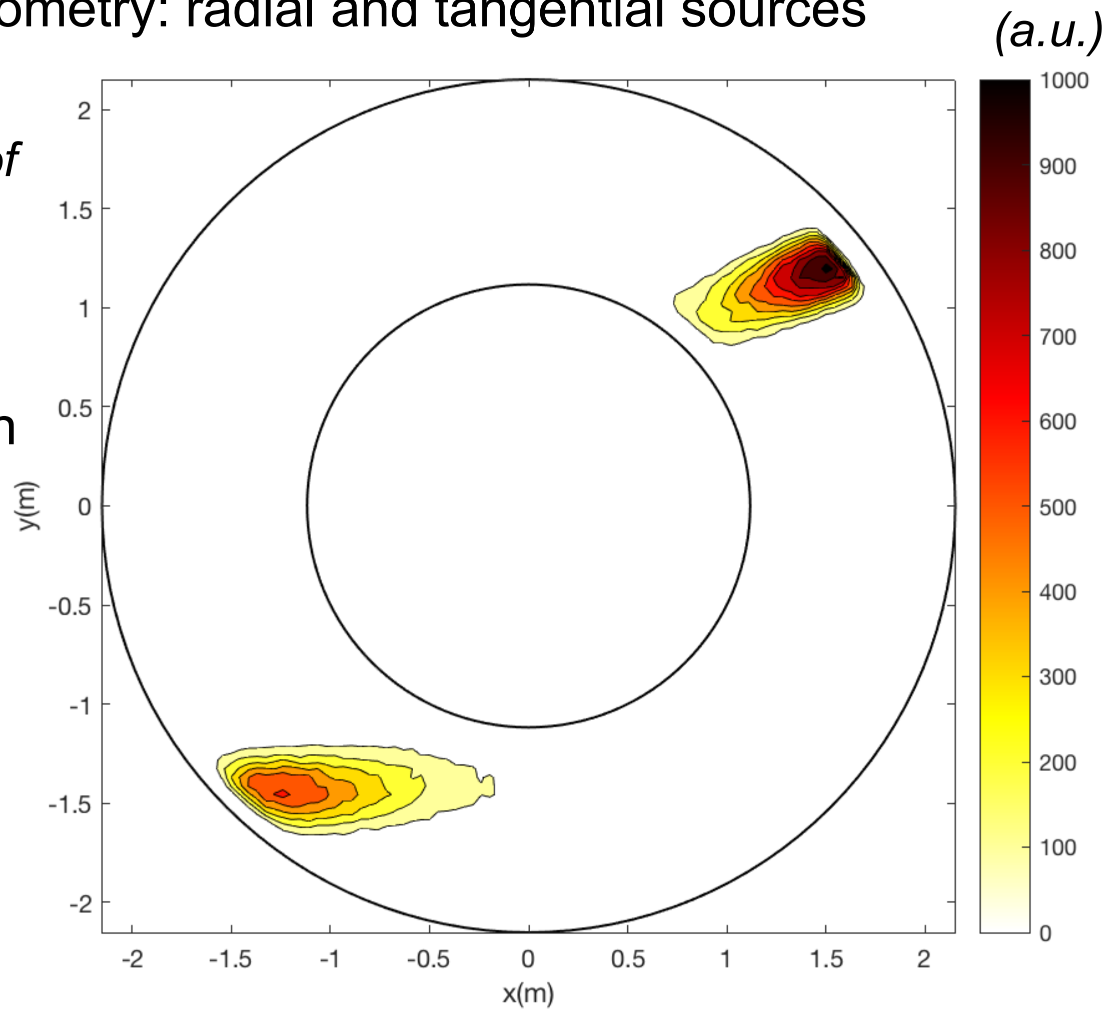
with ionization cross-section $\sigma = f(n_e, T_e, Energy)$ → fit takes into account atomic physics *[Suzuki PPCF98]*

→ When $1 - P(l) <$ *random threshold*: particle is ionized.

NBI-induced fast ion source validated for AUG case

→ Experimental geometry and equilibrium profiles from AUG shot #23076
[Acknowledgement to Giovani Tardini, IPP Garching]
→ Experimental NBI source geometry: radial and tangential sources

Integrated number of injected particles, top view



→ Good agreement of ionization with NUBEAM calculation
[Asunta CPC15]

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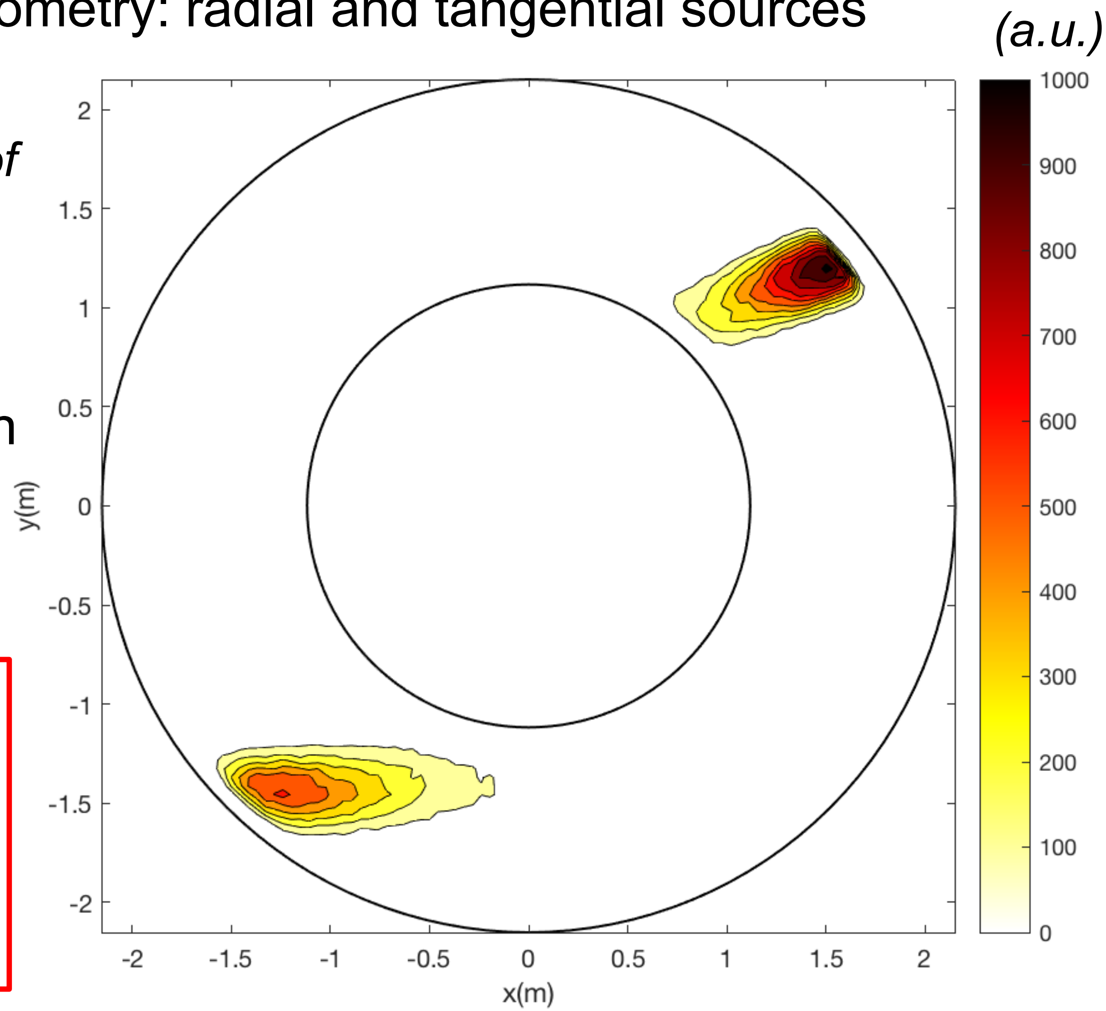


→ Good agreement of ionization with NUBEAM calculation *[Asunta CPC15]*

NBI + collisions allow us to reproduce experiments in modeling of fast particle-MHD interaction

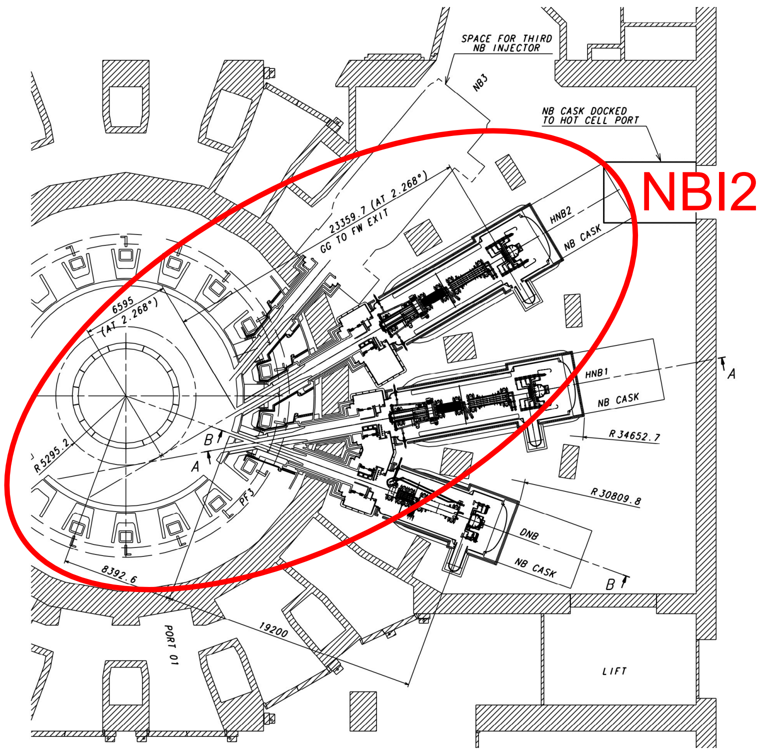
- Fishbone/sawtooth dynamics using slowing-down fast-particle distribution *[Brochard PhD thesis 2019]*
  - → Tool for preliminary studies: linear fishbone model
  - → Fishbone dynamics with XTOR-K

- MHD interaction with NBI-induced fast particles
  - → New features in XTOR-K: collisions and NBI
  - → Ongoing work towards fishbone induced by NBI
    - Initial condition: equilibrium bulk plasma :
      99% fluid (MHD) + 1% kinetic (maxwellian)
    - 2 steps:
      1/ NBI ON + collisions ON. Constant MHD fields
      2/ NBI OFF, MHD evolution ON, collisions still ON.

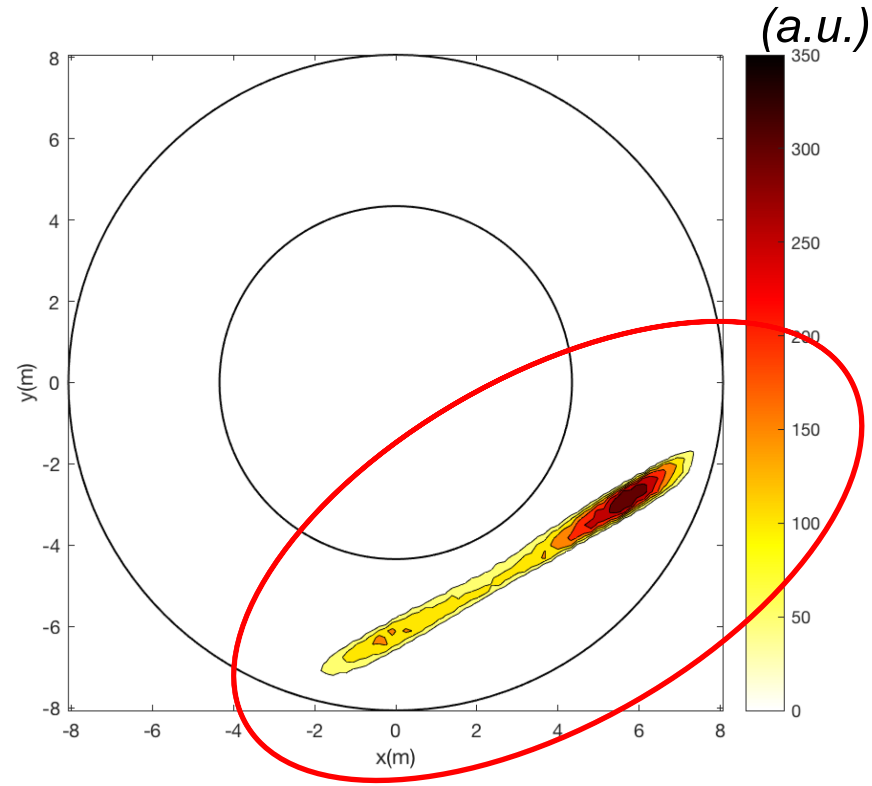
ITER-like 15MA simulation with 1NBI: step#1

- 1st step: NBI ON + collisions ON. Constant MHD fields

→ 1 NBI tangential source, P_{NBI}=16.5 MW, $E_{particle}$=1MeV
→ Increased collision rate and P_{NBI} x10^3-10^4 to reduce computation time



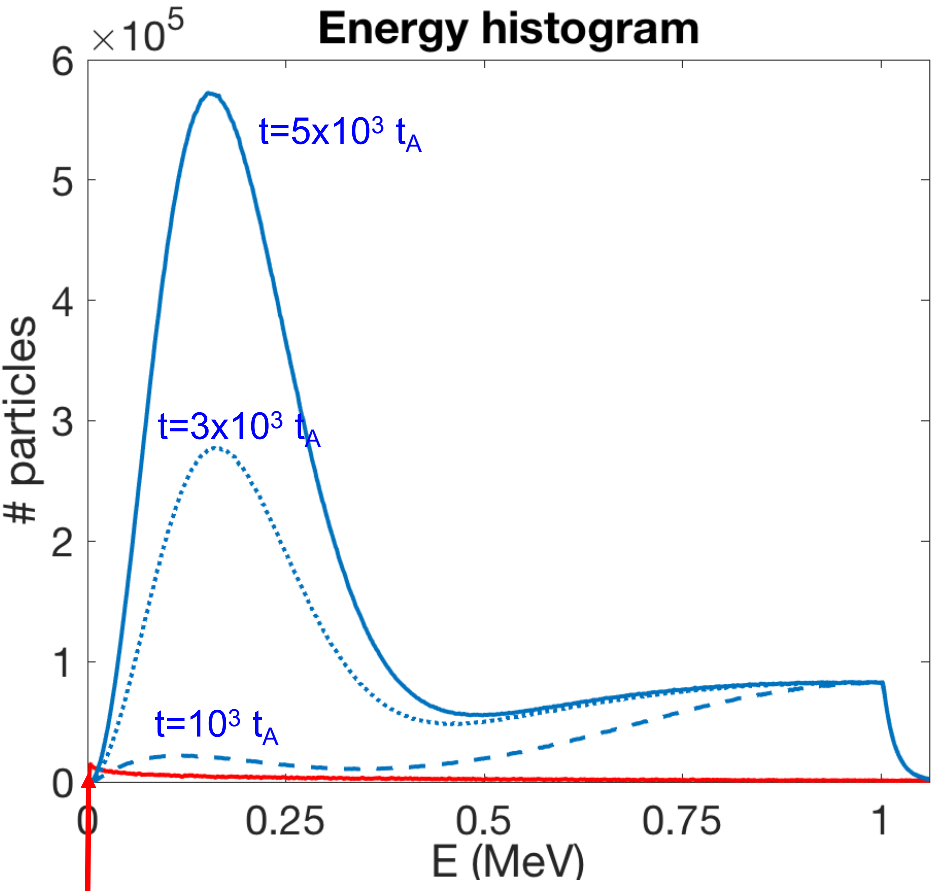
[ITER EDA documentation series No. 24, ITER technical basis, IEAE 2002]



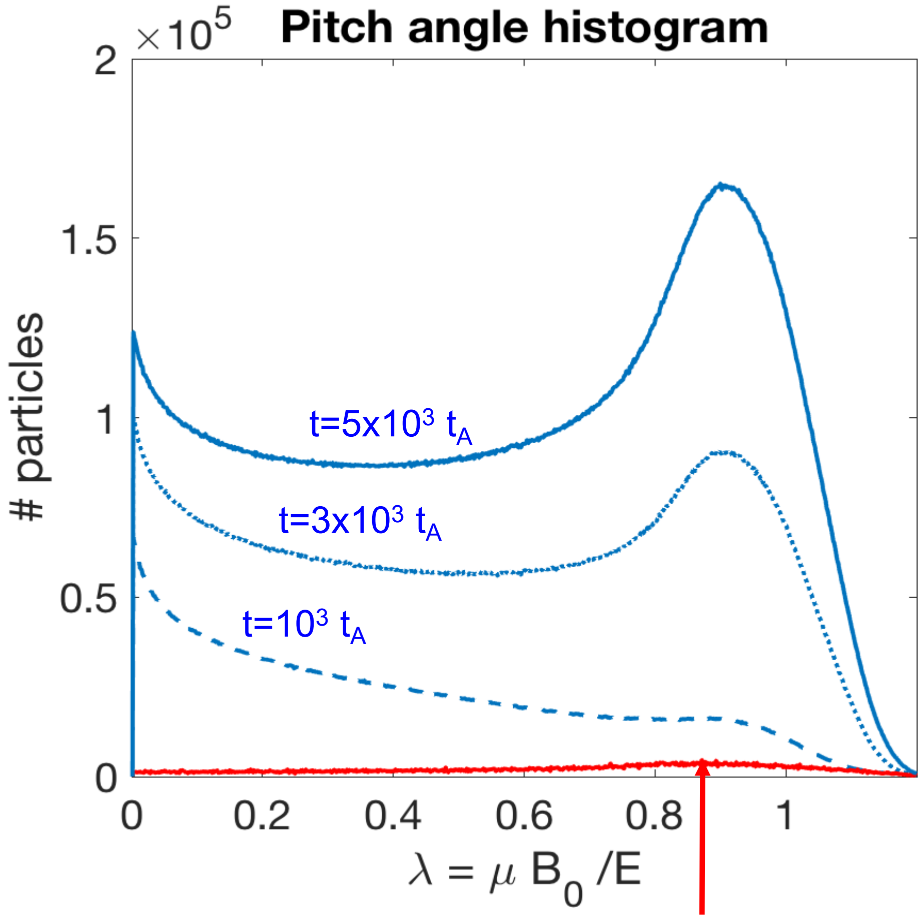
Integrated number of injected particles, top view

Step#1: relaxation towards realistic slowing-down distrib.

➢ 1st step: NBI ON + collisions ON. Constant MHD fields

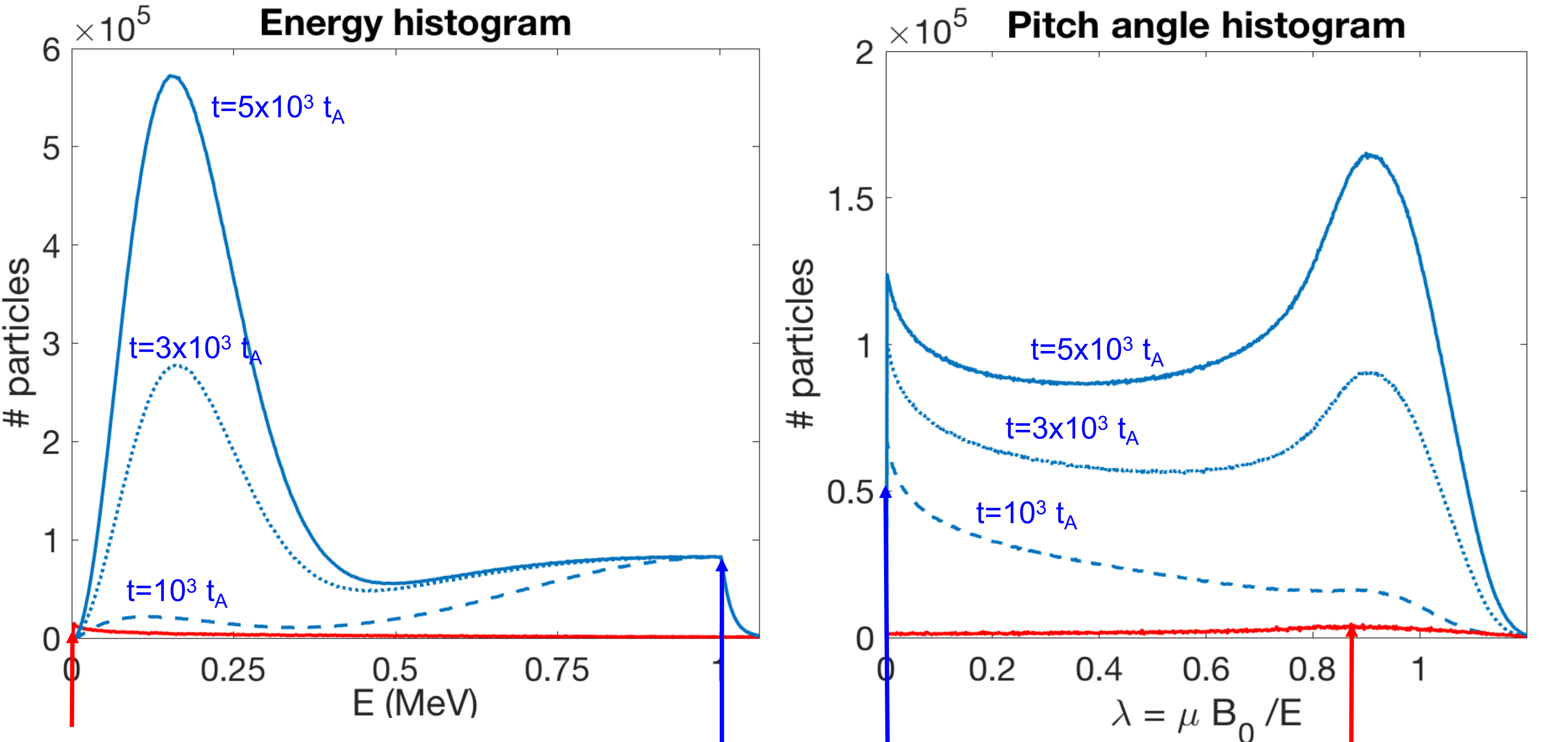


Initial 1% bulk=kinetic



Step#1: relaxation towards realistic slowing-down distrib.

- 1st step: NBI ON + collisions ON. Constant MHD fields

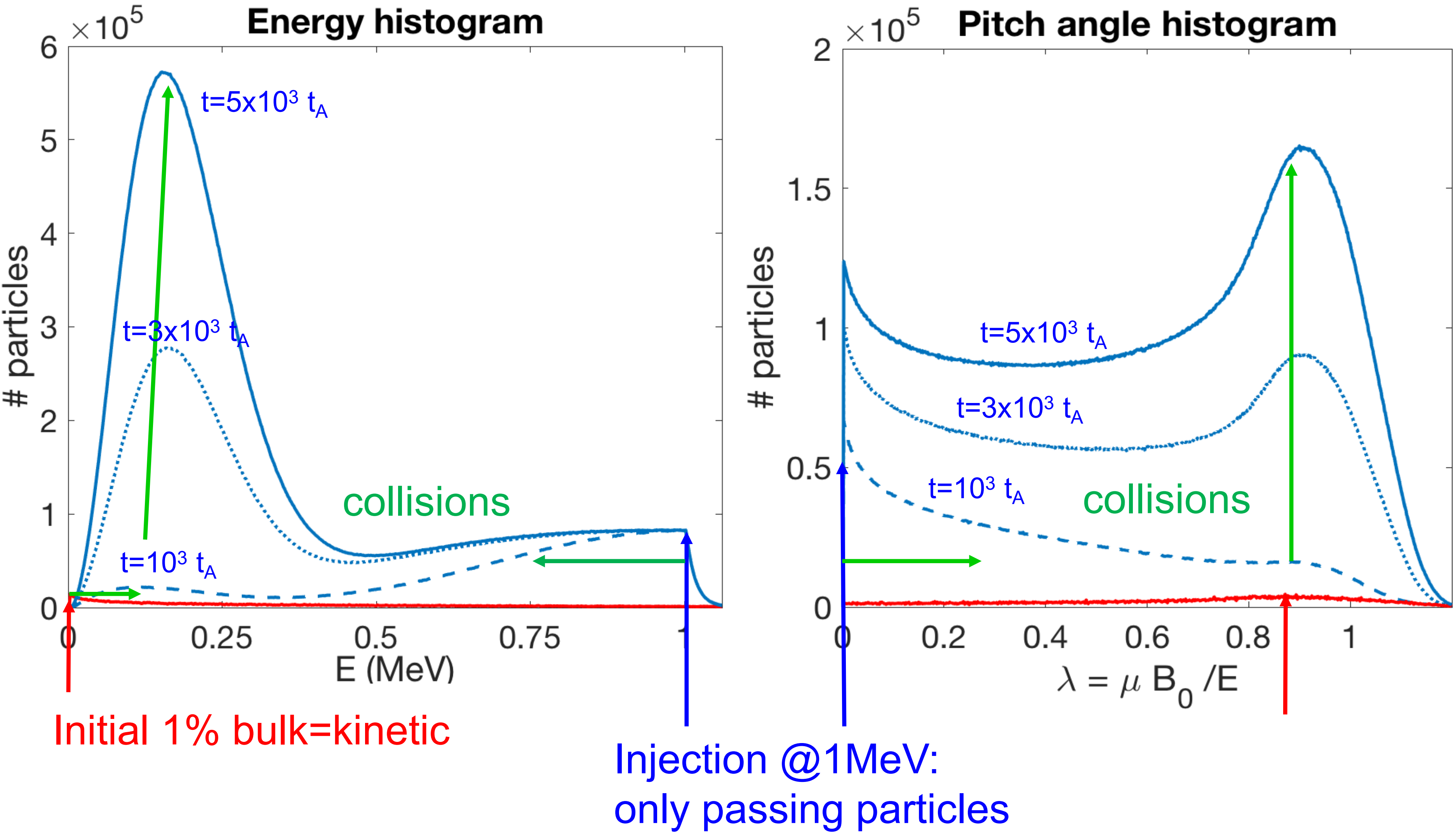


Initial 1% bulk=kinetic

Injection @1MeV:
only passing particles

Step#1: relaxation towards realistic slowing-down distrib.

- 1[st] step: NBI ON + collisions ON. Constant MHD fields



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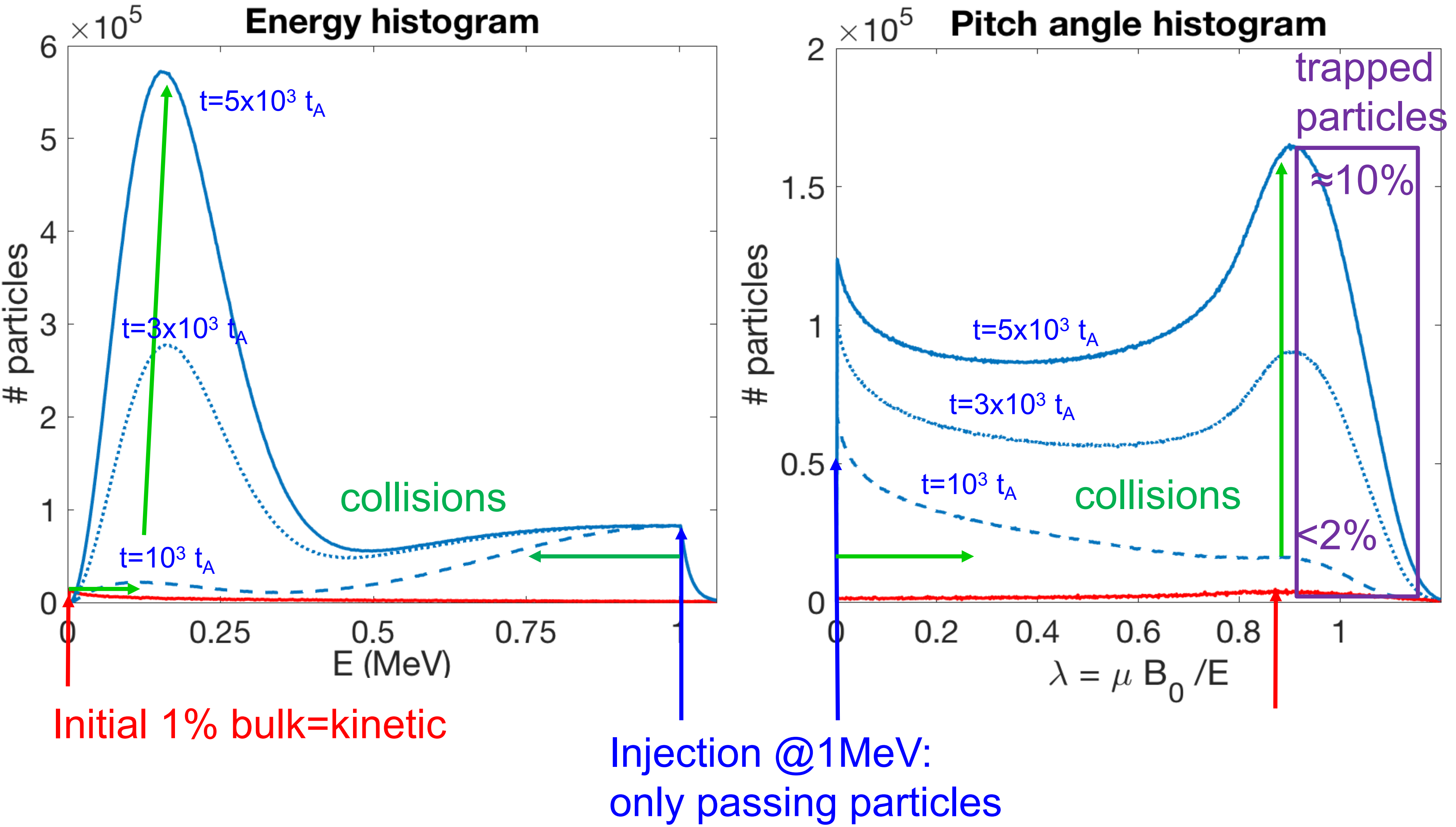

Step#2: Case #1: reduced E_{NBI} and bulk density: no effect of NBI on kink/fishbone stabiliity

- 2nd step: NBI OFF, MHD evolution ON, collisions still ON.
  → self-consistent interaction between MHD and NBI-injected fast particles
  → Goal 🥅: check if NBI can induce fishbone in ITER

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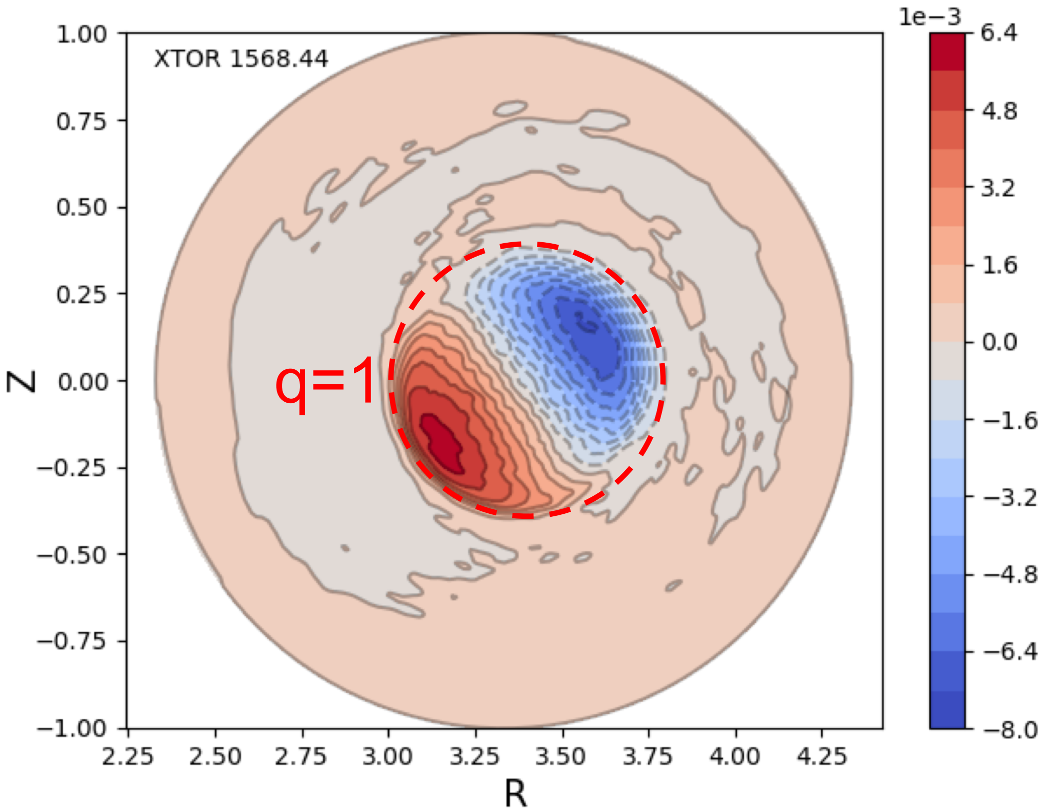
- Test case #1: ~~E=1MeV~~ → E=100keV ; ~~$n_e=1x10^{20}m^{-3}$~~ → $n_e=3x10^{19}m^{-3}$



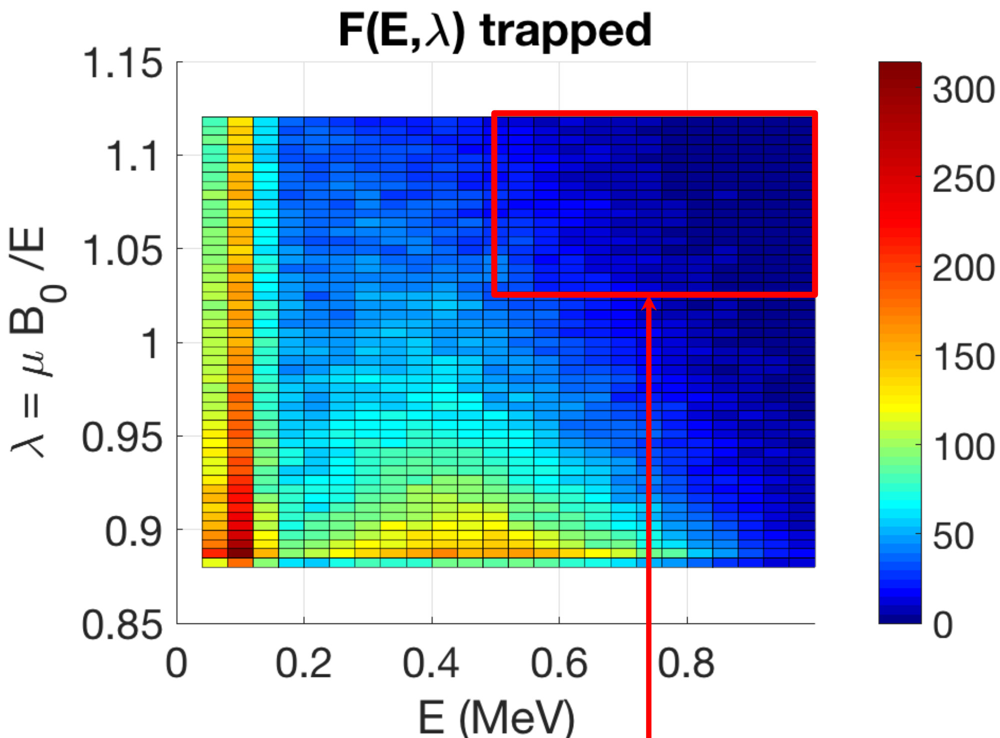
Perturbation of ion pressure

→ "classical" internal kink mode (n=1, m=1): same growth rate and dynamics as without NBI
→ no resonance between fast particles and n=1 mode

Step#2: Case #2: realistic E_{NBI} and bulk density: still no fishbone-resonant configuration

- 2^{nd} step: NBI OFF, MHD evolution ON, collisions still ON.
  → self-consistent interaction between MHD and NBI-injected fast particles
  → **Goal 🥅: check if NBI can induce fishbone in ITER**

- Test case #2: E=1MeV ; $n_e=1\times10^{20}m^{-3}$



Very few particles in
fishbone-resonant zone: still internal kink

Step#2: Case #2: realistic E_{NBI} and bulk density: still no fishbone-resonant configuration

- 2^{nd} step: NBI OFF, MHD evolution ON, collisions still ON.
  → self-consistent interaction between MHD and NBI-injected fast particles
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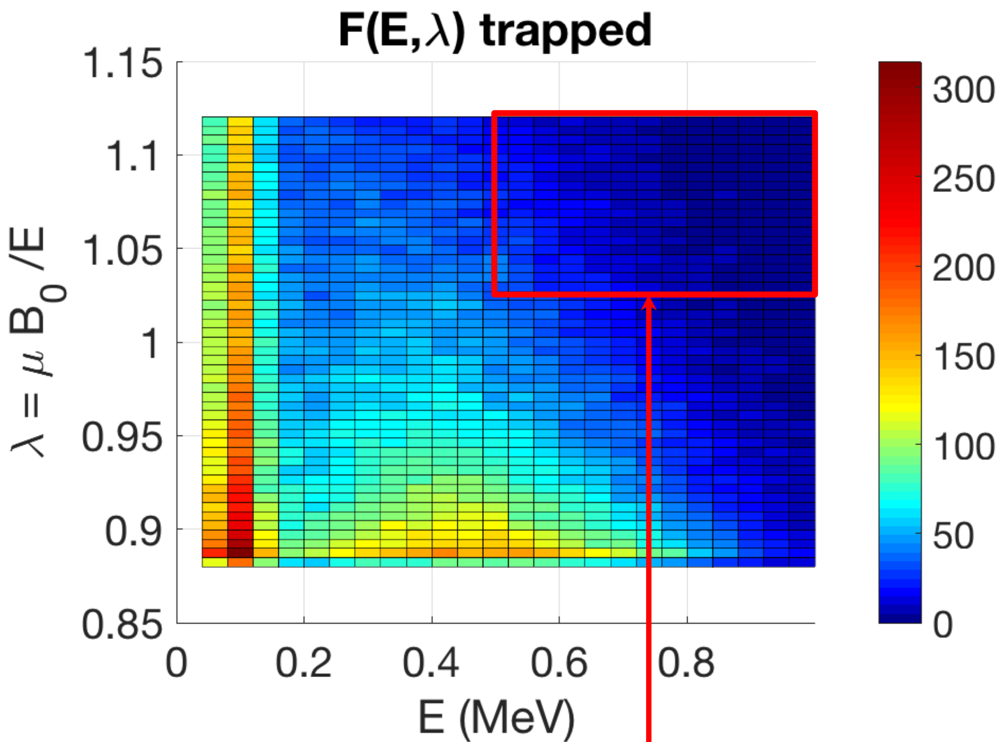
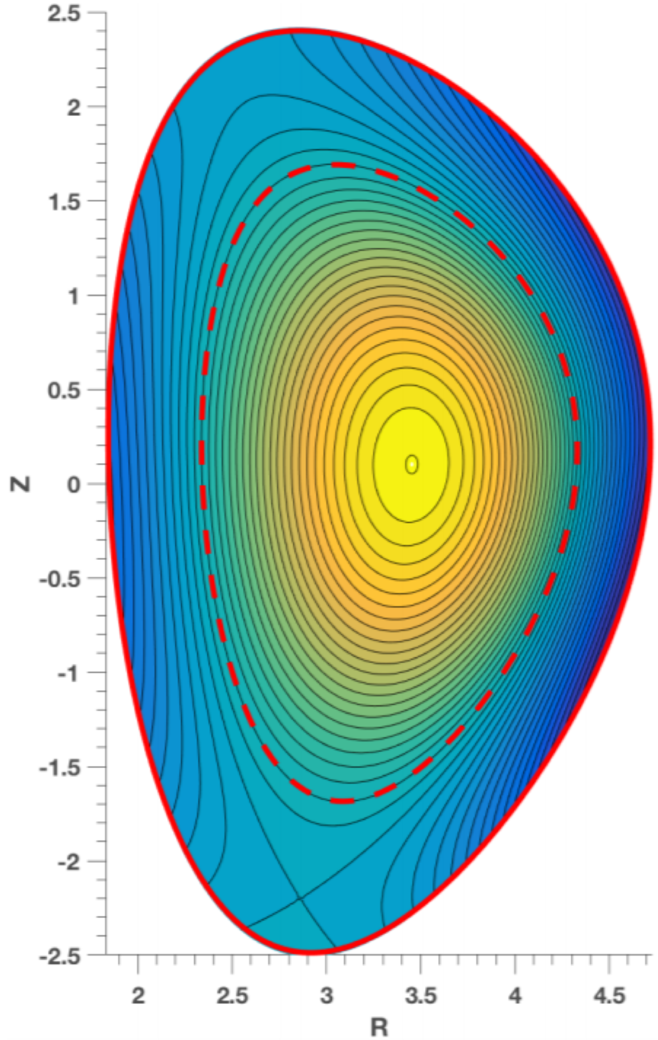


Very few particles in
fishbone-resonant zone: still internal kink

Next steps:
1/ Inject NBI-induced distribution into linear model
→ predict fishbone-unstable conditions
2/ XTOR-K is ready for non-linear simulations

Additional work in progress: extend computational domain, including SOL, coils and wall

- Enabling Research project "kinetic MHD and control opportunities": *PI Timothée Nicolas*



→ Domain extension validated in vacuum *[A. Marx PPCF2017]*

→ Under development for plasma with resistive wall

→ First external kink modeling ongoing

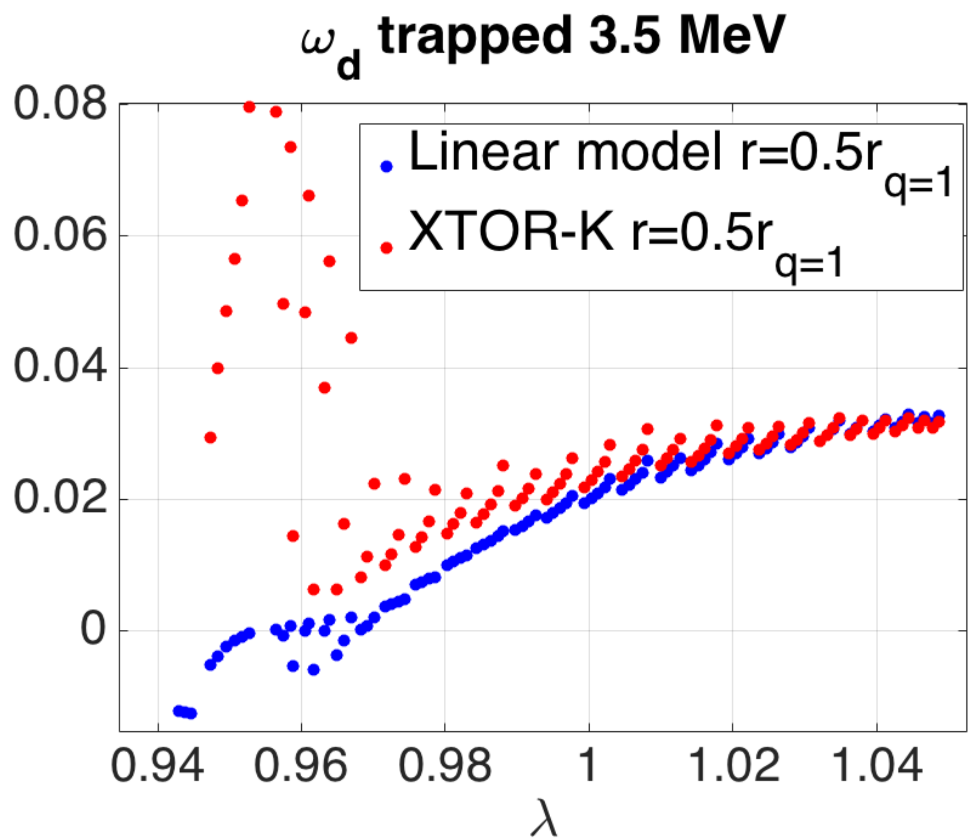
Conclusion

- XTOR-K : hybrid MHD + kinetic
  → new features: linear fishbone model for predictions, collisions, NBI
  + ongoing: extend computational domain to SOL and wall
  → allows to model realistic tokamak physics in the core + soon at the edge

- Linear model + XTOR-K with slowing-down fast particle distrib:
  → ITER: Fishbone unstable below expected β_{fast} threshold
  → chirping of fishbone with resonant transport

- XTOR-K with NBI and collisions:
  → Realistic fast particle distribution relaxes towards slowing-down
  → ITER: on the way to check if NBI can induce fishbone

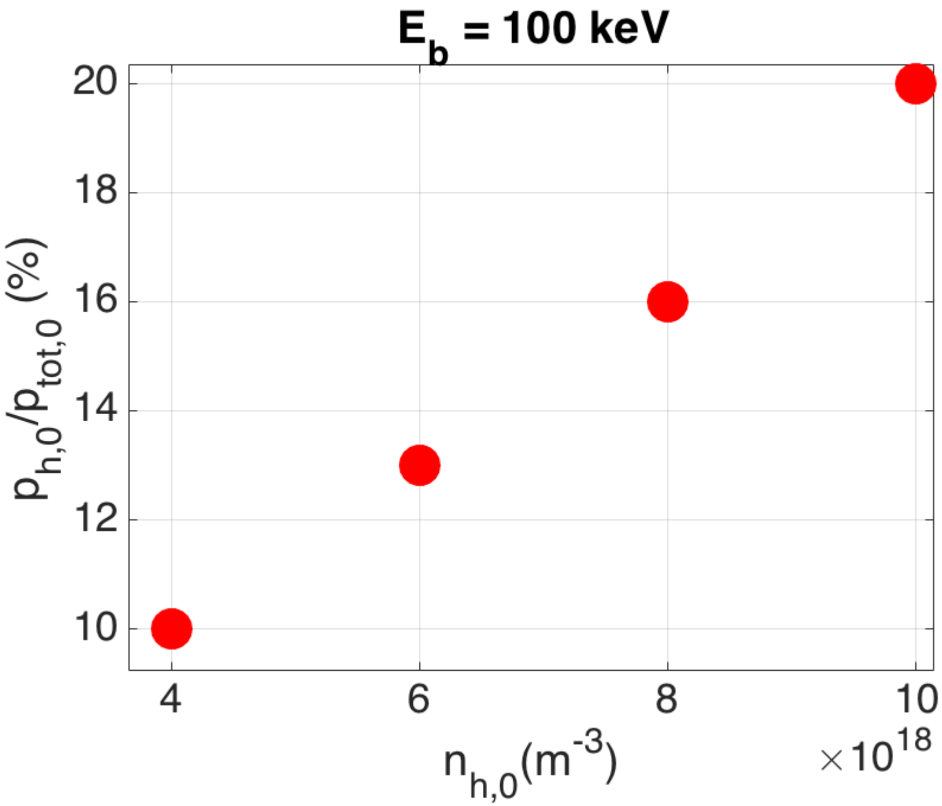
THIN ORBIT WIDHT ASSUMPTION INCORRECT FOR E_b > 1MeV



- At **high energies**, the **linear model** thin orbit width approximation **breaks down**

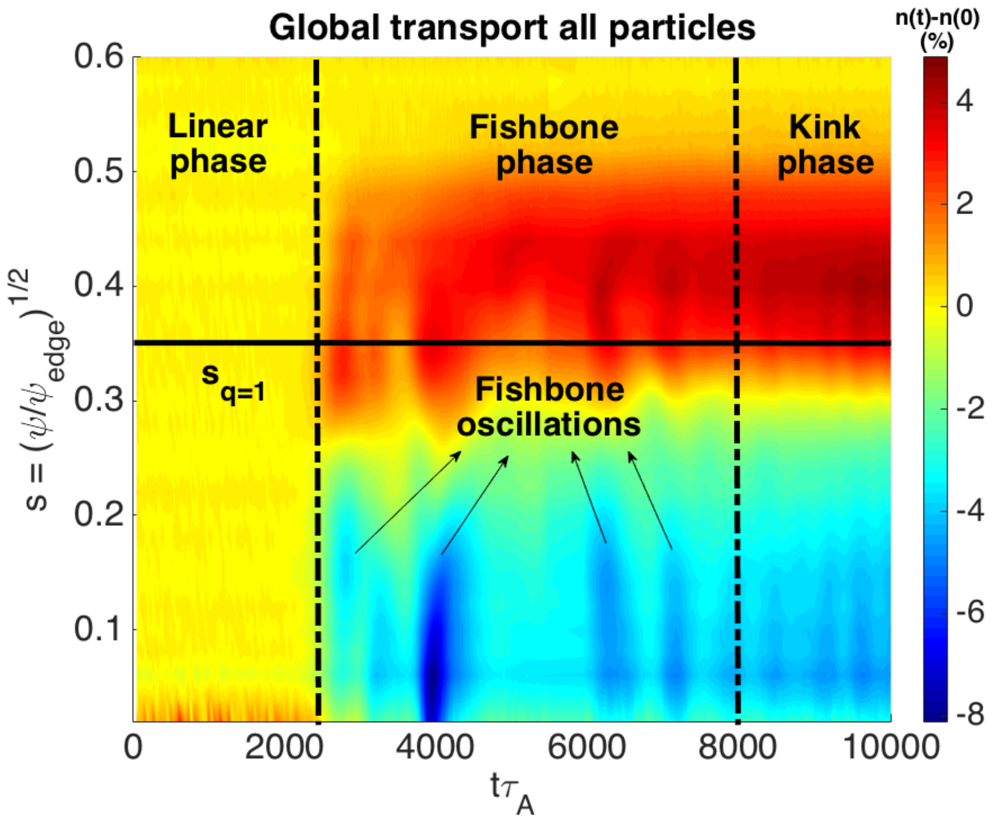
- **Linear verification** cannot be performed for E_b **> 1 MeV**

LOW EP PRESSURE APPROXIMATION NOT VALID AT E_b < 1MeV



- For low **birth energy** (< 1MeV), **fishbones triggered** with $p_h \sim p_{tot}$
- **EP pdf** with E_b **< 1MeV** not suitable for **linear verification**

WEAK OVERALL TRANPORT IN ITER



- **Overall EP transport** in core plasma around **6%** in the fishbone phase
- **Effects** of the alpha **fishbone** instability on fusion performances **limited**
- **Fast mode chirping** may **prevent** to **transport** large amount of **EP**

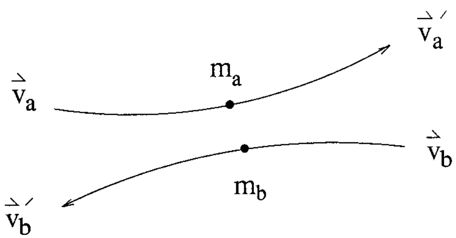
$$\frac{\mathrm{d}f}{\mathrm{d}t} = \mathcal{C}[f,f]$$

Binary collisions

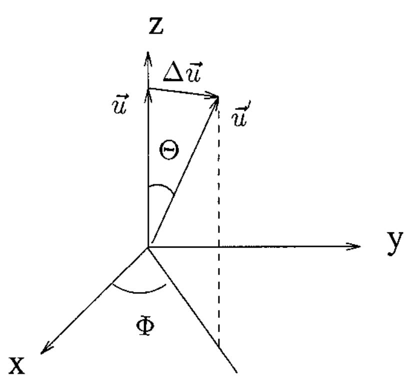
$$\mathcal{C}[f,f] = \frac{(Ze)^4 \boldsymbol{\Lambda}}{8\pi\varepsilon_0^2 m}\frac{\partial}{\partial \boldsymbol{v}} \cdot \int \bar{U}(\boldsymbol{v}-\boldsymbol{v}') \cdot \left(\frac{f(\boldsymbol{v}')}{m}\frac{\partial f(\boldsymbol{v})}{\partial \boldsymbol{v}} - \frac{f(\boldsymbol{v})}{m}\frac{\partial f(\boldsymbol{v}')}{\partial \boldsymbol{v}'}\right) \mathrm{d}^3\boldsymbol{v}'$$

$$\boldsymbol{\Lambda} = \log\left(\frac{b_{\max}}{b_{\min}}\right)$$

$$\mathcal{C}[f,f] = -\frac{\partial}{\partial \boldsymbol{v}} \cdot \left(\mathbf{F}f - \frac{1}{2}\frac{\partial}{\partial \boldsymbol{v}} \cdot (\bar{\mathbf{D}}f)\right)$$



$$\mathbf{F} = \frac{\langle \delta \boldsymbol{v} \rangle}{\delta t} \qquad \bar{\mathbf{D}} = \frac{\langle \delta \boldsymbol{v} \delta \boldsymbol{v} \rangle}{\delta t}$$



- ❑ Select the two angles so that on average, friction and dissipation have their theoretical values
- ❑ Calculation is O(N)
- ❑ Equivalent to Landau-Fokker-Planck [Bobylev PRE 2000]

Binary collisions are NOT Rutherford collisions!!

Improvement of code execution thanks to domain decomposition, even including collisions

Domain cloning

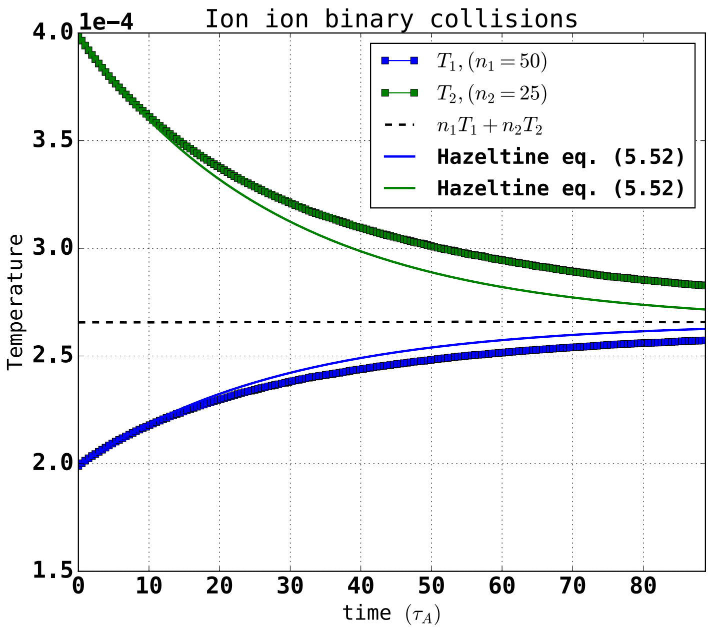
- Move: ~30s
- Deposition: <1.5s
- Nonlinear solver: ~3s
- Total: ~36s/time step

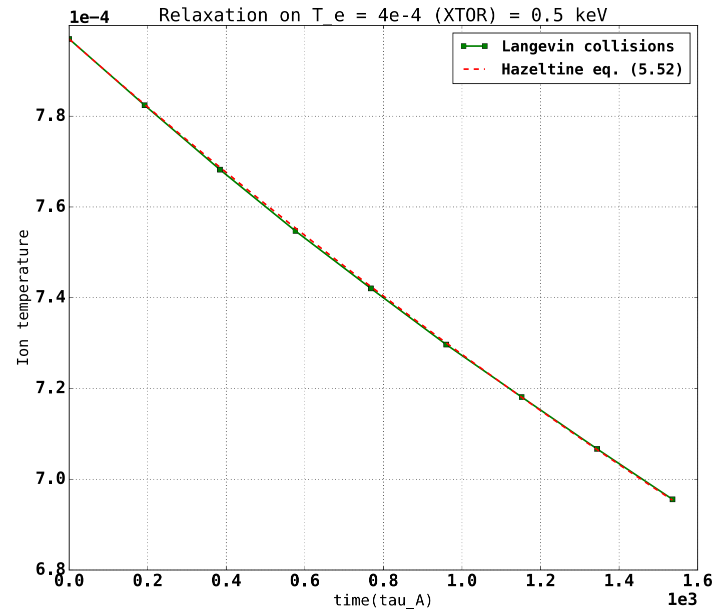
Domain decomposition

- Move: ~11.5s
- Deposition: >1.5s
- Nonlinear solver: ~3s
- Collisions: <0.1s
- Total: ~21s/time step

- The acceleration is only due to
  - Avoided cache miss
  - Change of field advance (done inside the loop to avoid one dcopy per particle step)
- No optimization to adapt to domain decomposition of
  - Particle deposition
  - MPI reduce

Inter- and intra-species collisions





- Inter-species binary collisions
- Energy conservation is only statistically guaranteed, because of weight difference **[Nanbu JCP 1998]**
- Conservation is exact in the case of intra-species collisions

- Langevin collisions on the electrons
- Electrons are assumed at rest (otherwise incompatibility with artificially high resistivity)

Neoclassical tests difficult

- A priori the code contains ion neoclassical physics, in particular if the main ion is mainly kinetic. However with a full-f description, PIC noise is very large on velocity.

$$\frac{\Delta V}{V} = \frac{1}{\sqrt{N}} \frac{\sqrt{\langle \overline{x}^2 \rangle}}{\langle x \rangle} \qquad \frac{\Delta T}{T} \simeq \frac{\sqrt{2}}{\sqrt{N}}$$

Velocity PIC noise is amplified, compared to temperature, by a large factor:

$$\frac{v_{th}}{v} \underset{v \sim v_i^\star}{\sim} \frac{L_T}{\rho} \propto T^{-1/2}$$

- For the moment, not enough numerical ressources to test the full neoclassical transport. Research ongoing.