Update on XTOR-K : Implementation of realistic EP distributions and application for BAEs in DIII-D

G. Brochard

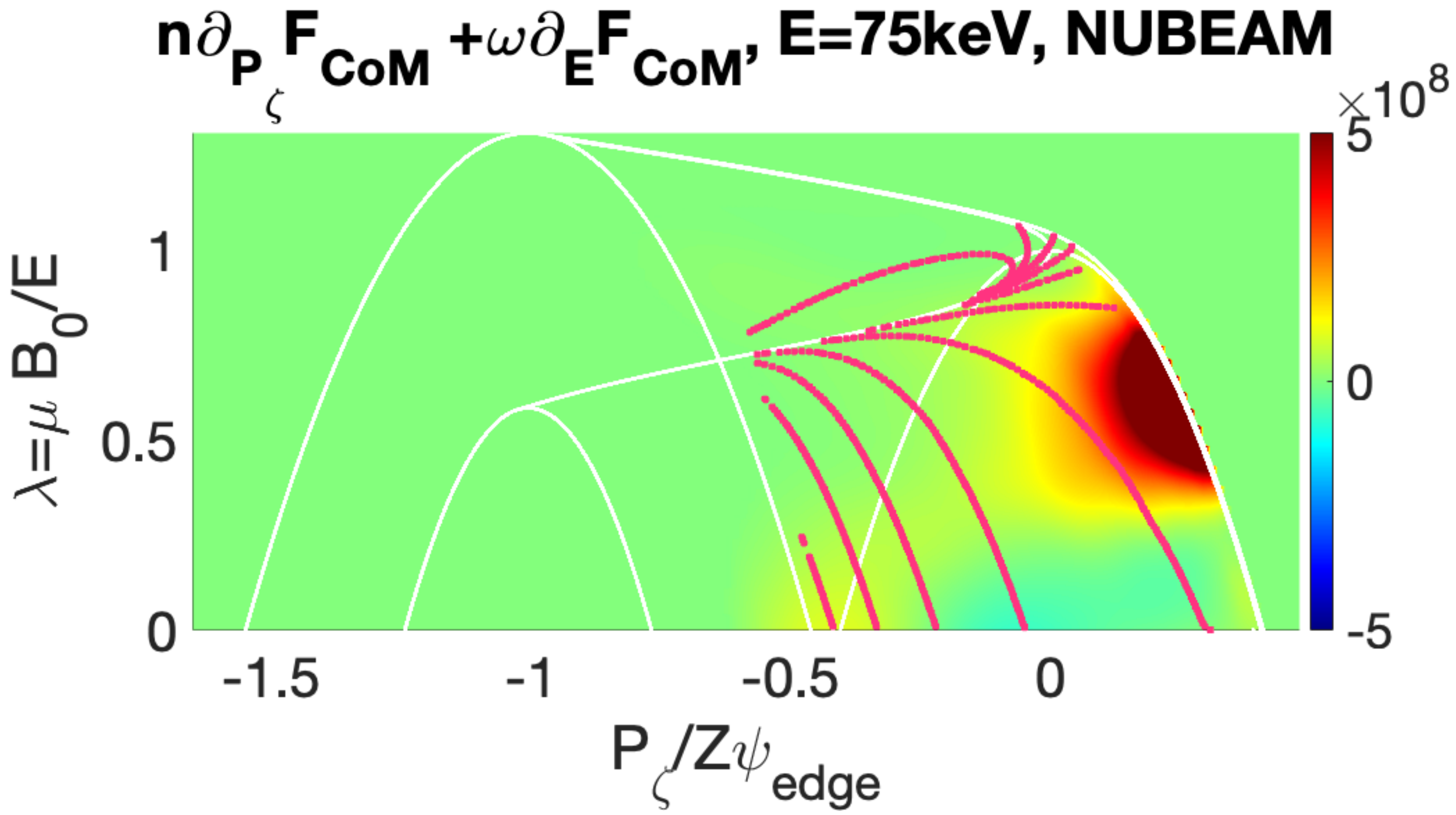
Importance of using realistic EP pdfs

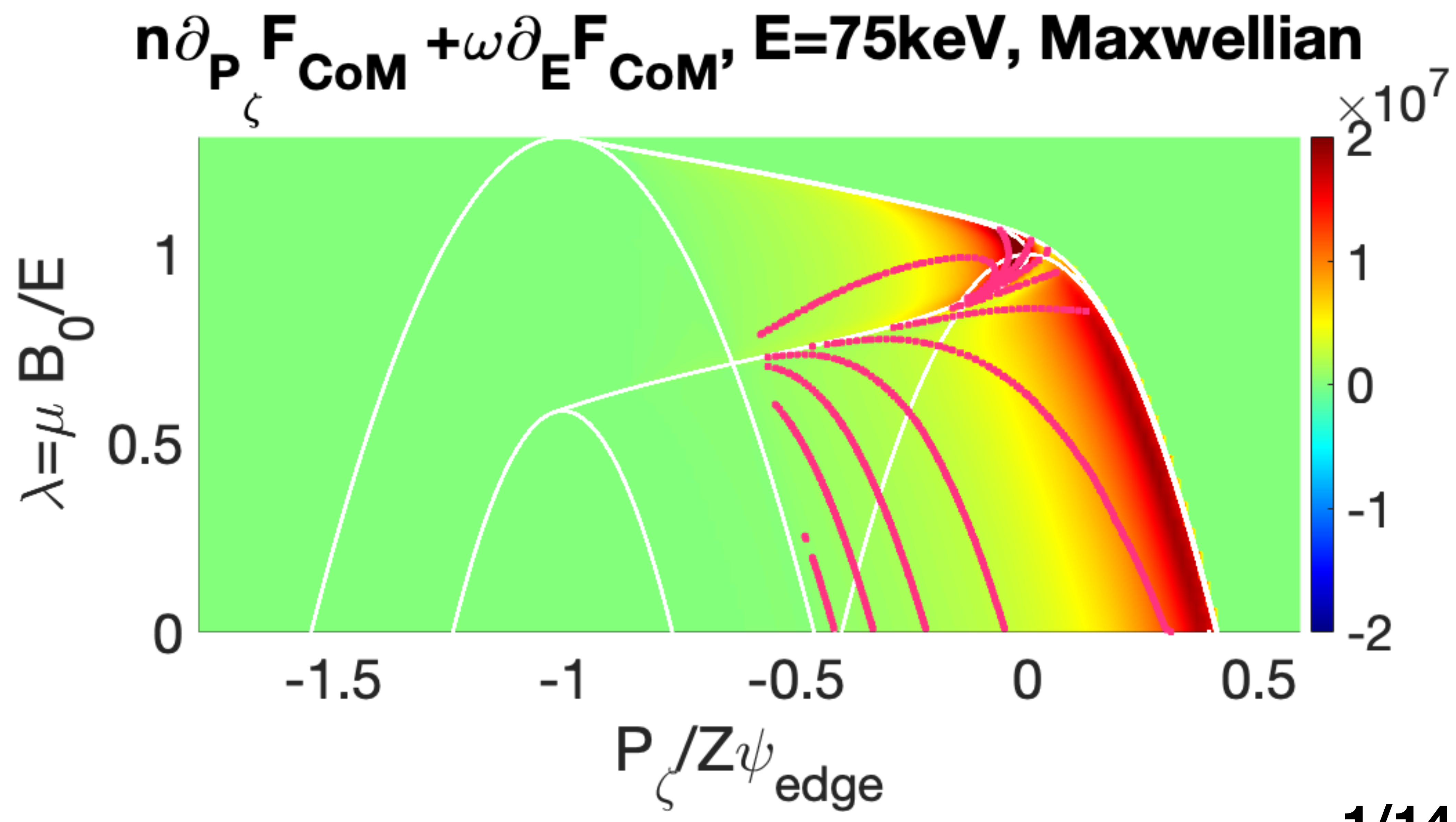
➢**Accurate transformation** of EP distributions towards **CoM space** enabled with the **EPCoM code [1]**

➢**CoM EP distributions** essential to model **realistically EPMs/AEs** linear stability and nonlinear dynamics

➢A **realistic EP drive** is **critical** in **predicting** the **beneficial operational domain** over which EP instabilities may **enhance confinement** in **current** and **future tokamaks [2-5]**

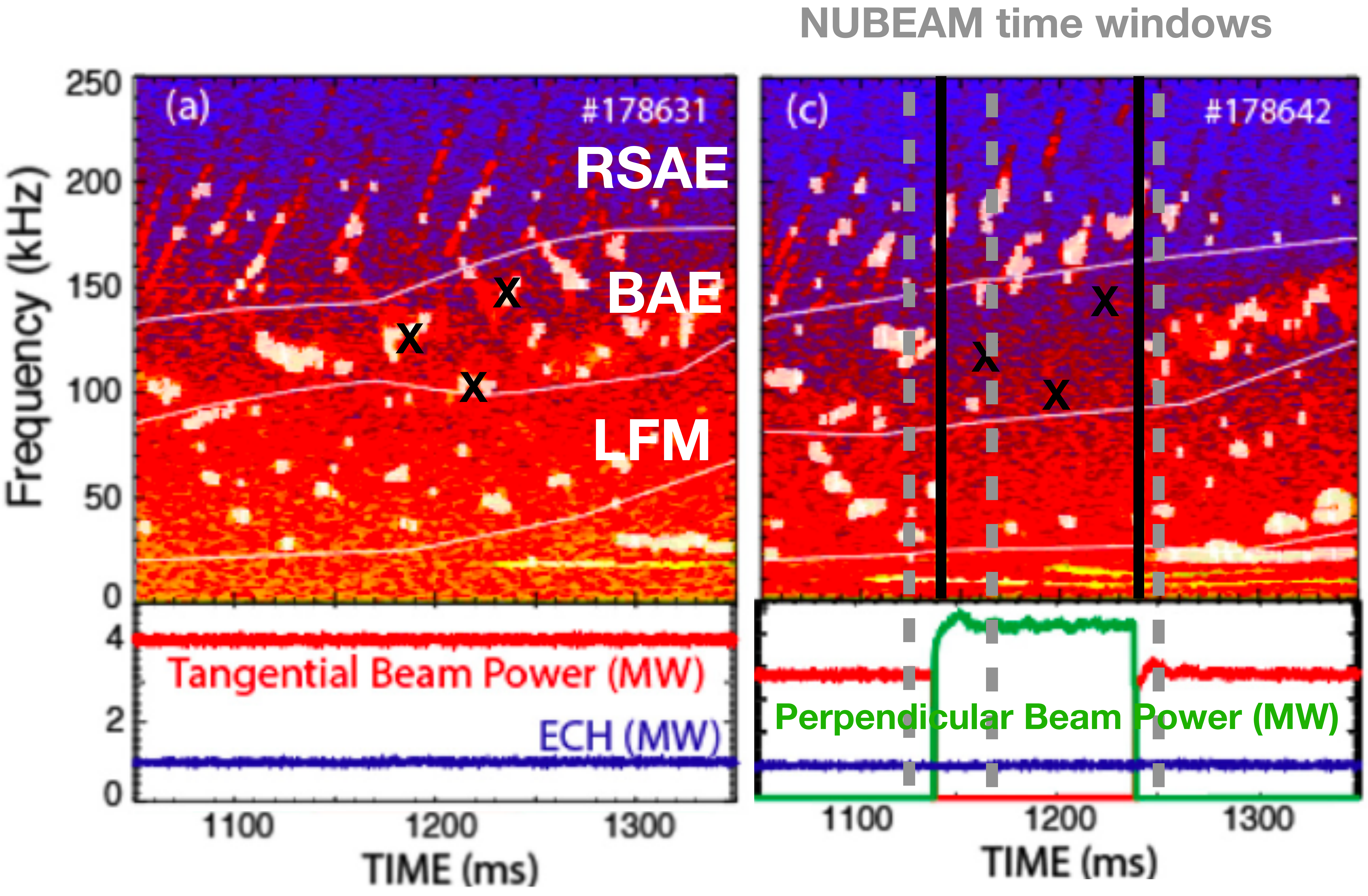
➢The **implementation** of **CoM distributions** in kinetic-MHD/ gyrokinetic codes and a **V&V against experiments** is an **essential first step** towards achieving confinement enhancement





[1] G. Brochard et al. 2026, *to be submitted to Comp. Phys. Comm.*
[2] S. Günter et al. 2001, *Nucl. Fusion*
[3] S. Mazzi et al. 2022, *Nat. Phys.*
[4] G. Brochard et al. 2024, *Phys. Rev. Lett.*
[5] J. Garcia et al. 2024, *Nat. Comm.*

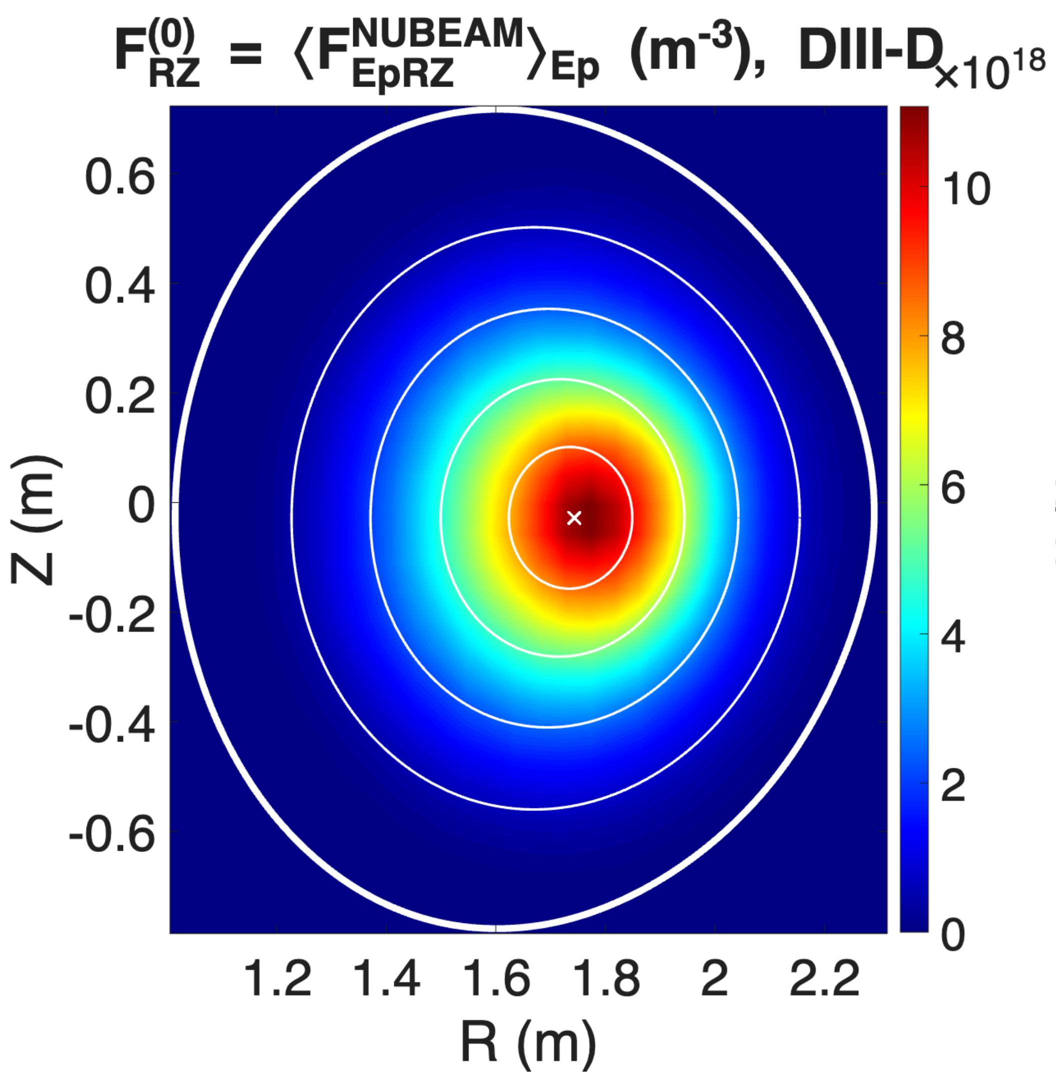
Variation of BAE stability in DIII-D discharges

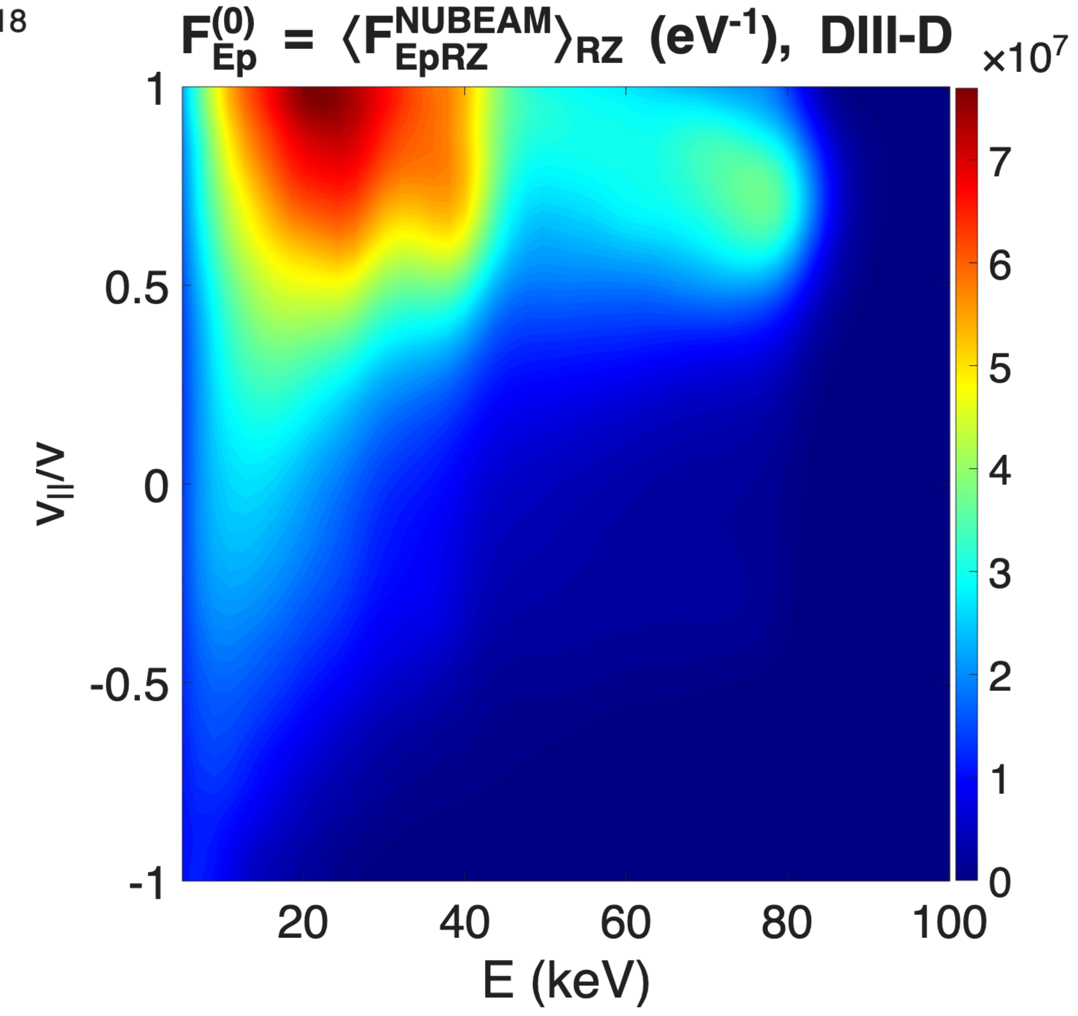


[1] W. W. Heidbrink et al. 2020, *Nucl. Fusion*
[2] W. W. Heidbrink et al. 2021, *Nucl. Fusion*

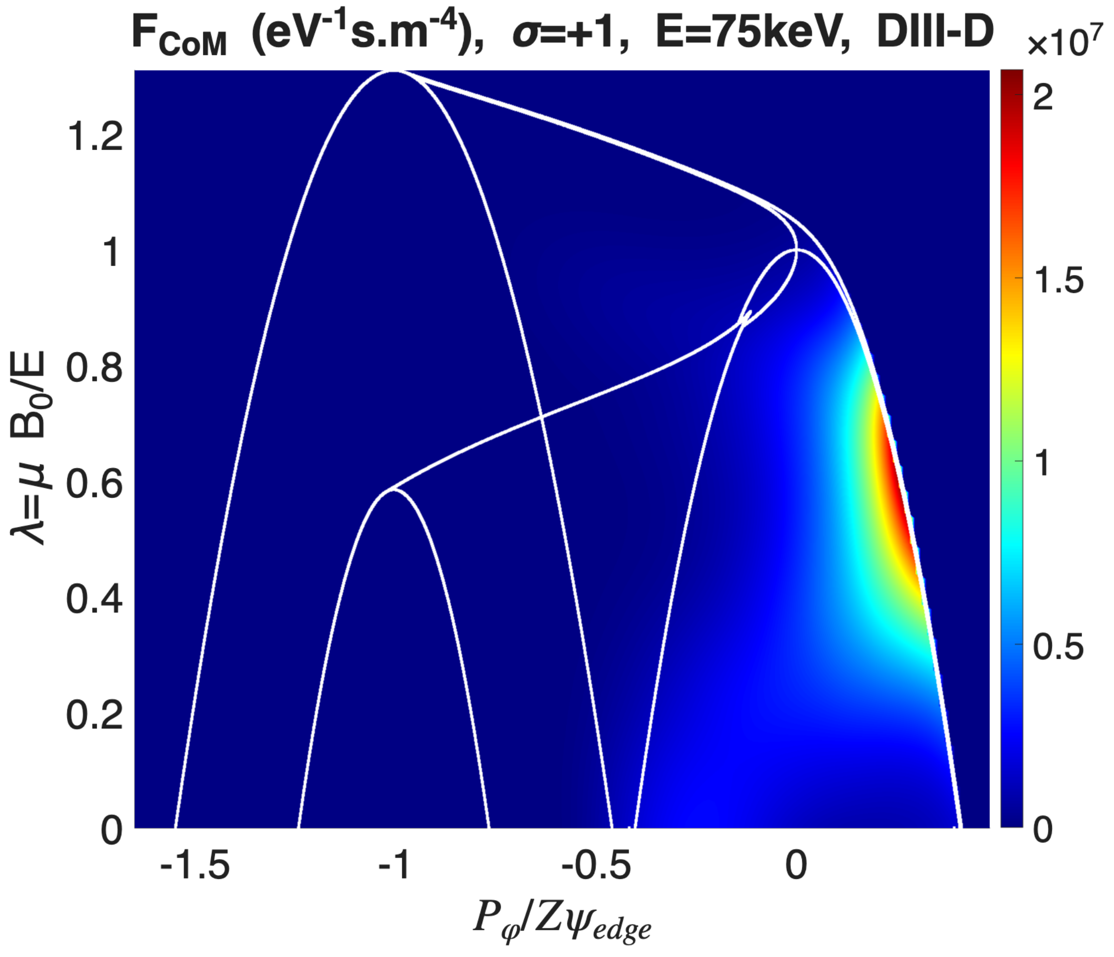
- ➢**DIII-D shot #178642** [1,2] has been selected to conduct a **first ITPA-EP cross-code V&V**
- ➢In **#178642**, **tangential** beams briefly swapped by **perpendicular** ones, providing a stable window for BAEs
- ➢**NUBEAM/EPCoM tandem** used to reproduce **CoM distributions** on **three time windows**
- ➢**Experimental validation** on DIII-D plasmas → **basis** for **realistic evaluation** of EP-driven mode stability in **ITER**
- ➢Four **gyrokinetic** (GTC, ORB5, LIGKA, GENE) and five **kinetic-MHD** (XTOR-K, M3D-C1, M3D-K, MEGA, JOREK) codes currently participate to this **benchmark activity**

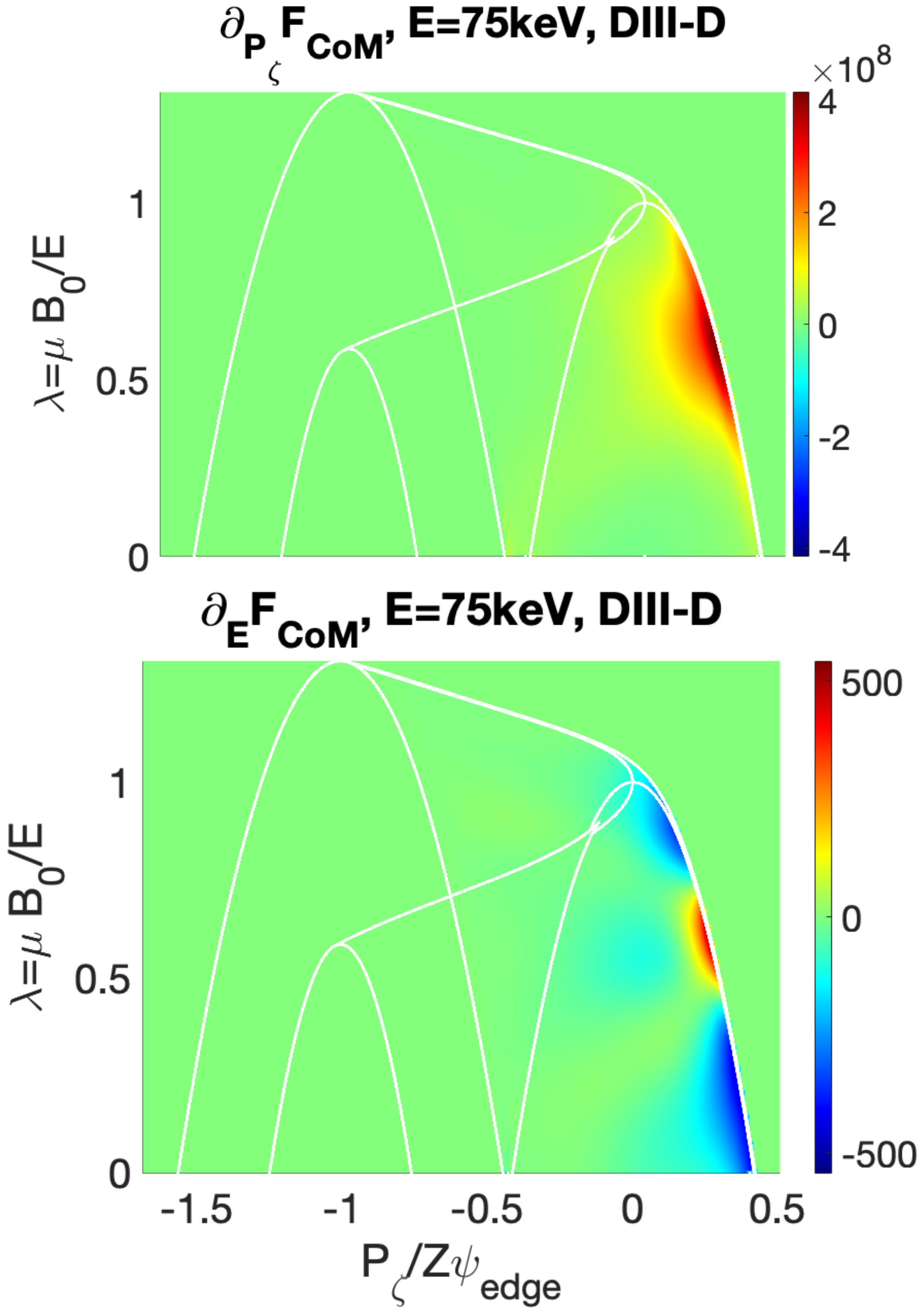
CoM spline input for EP28





EPCoM





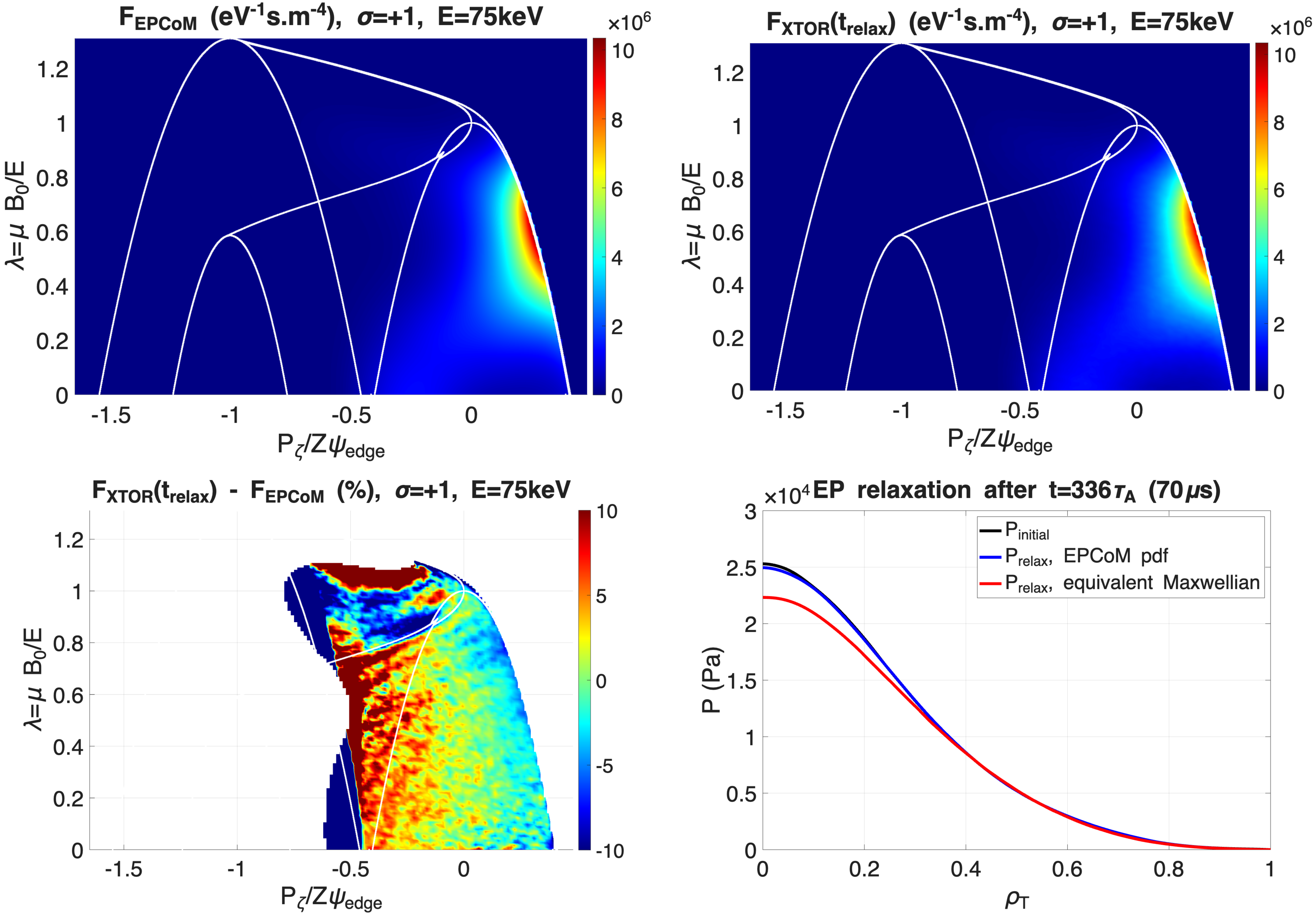
- ➢**EPCoM** is used to project the **NBI pdf** on a **3D CoM grid** $(P_\varphi, \lambda, E, \sigma = \pm 1)$

- ➢A **3D** $\mathscr{C}^2$ **B-spline** is created to compute F_{CoM} **and** $\partial_i F_{CoM}$ **anywhere in CoM space**

- ➢**Full-F codes** using **Eulerian/semi-Lagrangian methods** can **directly** read F_{CoM} for **grid initialisation**, while a **Monte-Carlo approach** is required to load marker for **PIC method**

- ➢For δF codes, the **equilibrium phase space gradients** $\nabla F|_{\mu,v_{||}}$, $\partial_{v_{||}} F|_{\mathbf{X},\mu}$ can be **evaluated** from **chain rule** operation, using $\partial_i F_{CoM}$ only : $\nabla F_{\mu,v_{||}} = \nabla P_\varphi|_{\mu,v_{||}} \frac{\partial F}{\partial P_\varphi} + \nabla \lambda|_{\mu,v_{||}} \frac{\partial F}{\partial \lambda} + \nabla E|_{\mu,v_{||}} \frac{\partial F}{\partial E}$

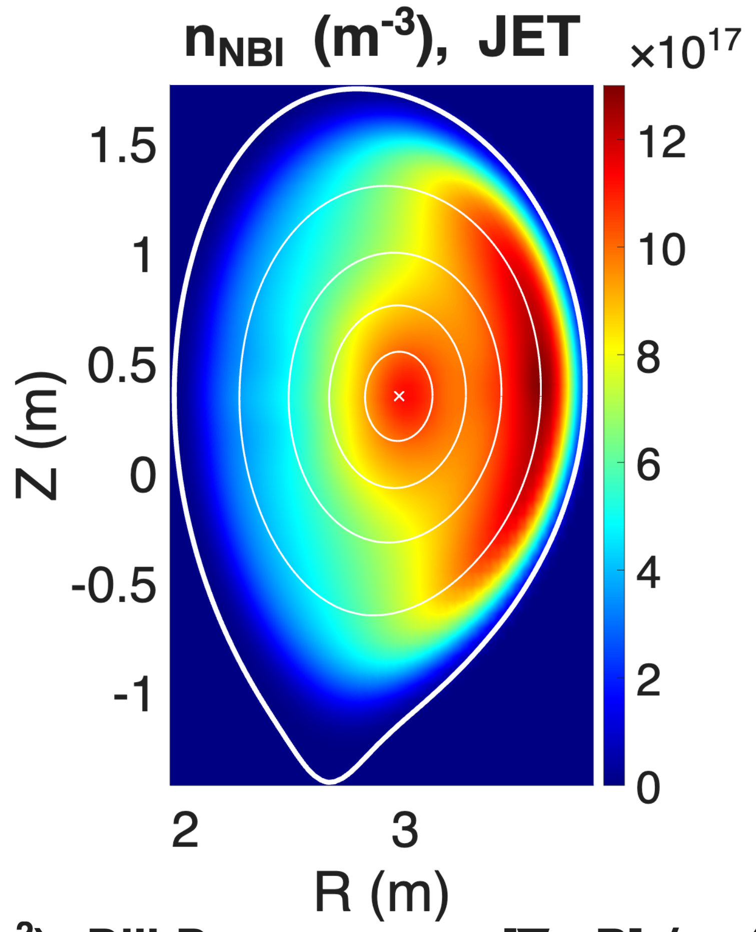
Initialization of EPCoM pdf in XTOR-K



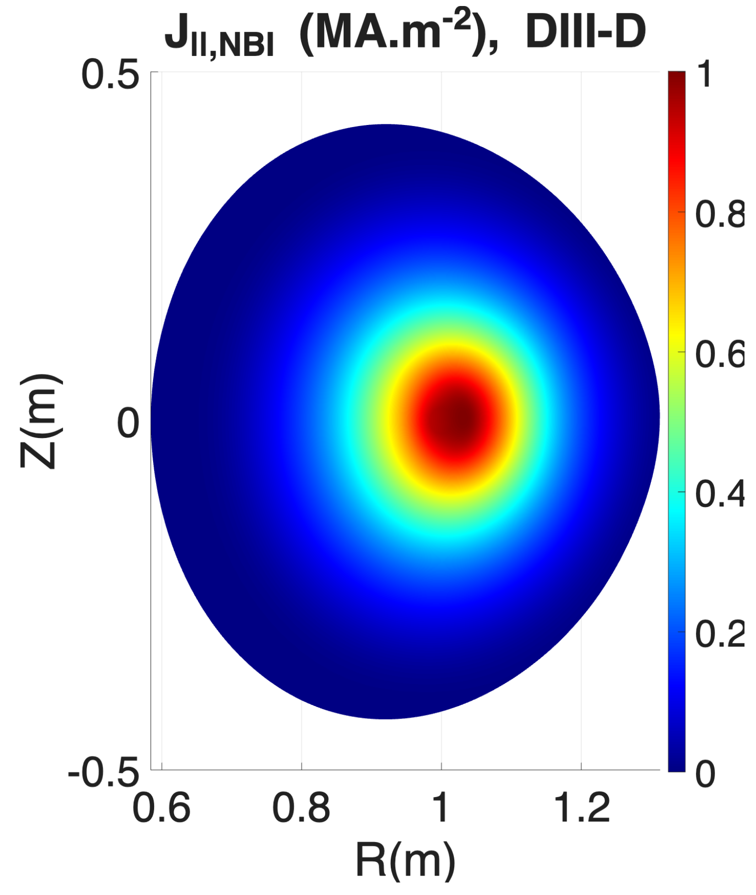
- ➢EPs can be loaded in XTOR-K using a **6D Monte-Carlo method**, pulling randomly (**X**, **V**), computing **CoM coordinates** and using F_{EPCoM} **as control function**
- ➢Using 256M markers, **EP loading is successful**
- ➢After $t_{relax} = 334\tau_A = 70\mu s$, **the EP pdf remains stationery,** as expected
- ➢**Comparatively**, the **equivalent Maxwellian** undergoes **significant relaxation**

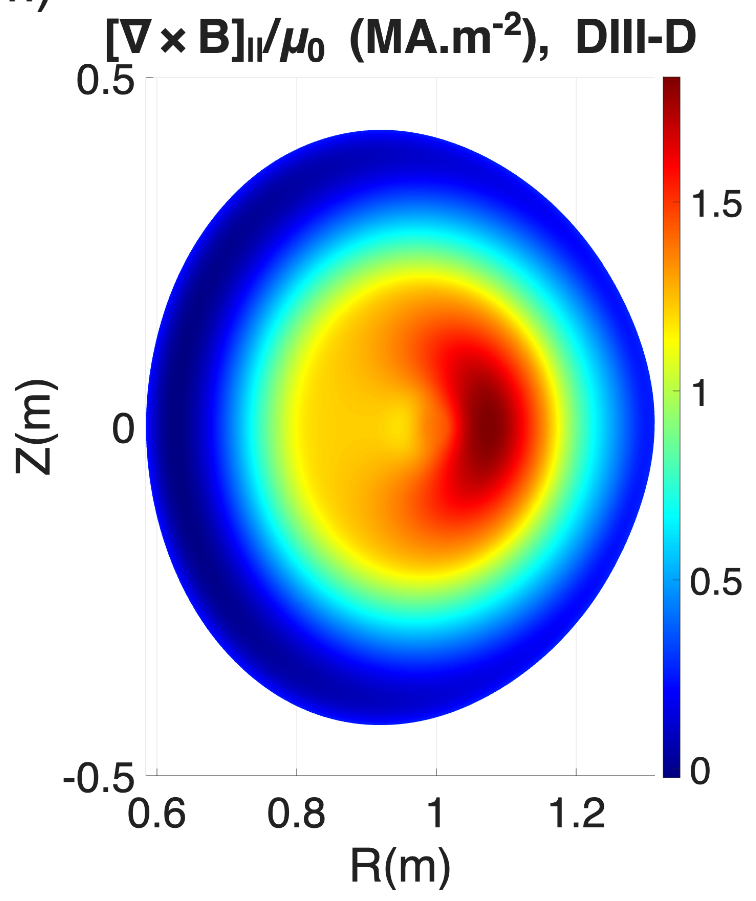
True kinetic equilibrium requirements

➢Since XTOR's kinetic module is **full-F**, a true **kinetic-MHD equilibrium** needs to be **initialised** at the **start of the simulation**, otherwise **blow-outs** may occur



➢**Quasi-neutrality** $n_e(\psi,\theta) = \Sigma_k Z_k n_k(\psi,\theta)$ is enforced strictly, for arbitrary 2D 0^{th} order kinetic moments $n_k(\psi,\theta) = \int F_k d^3\mathbf{v}$

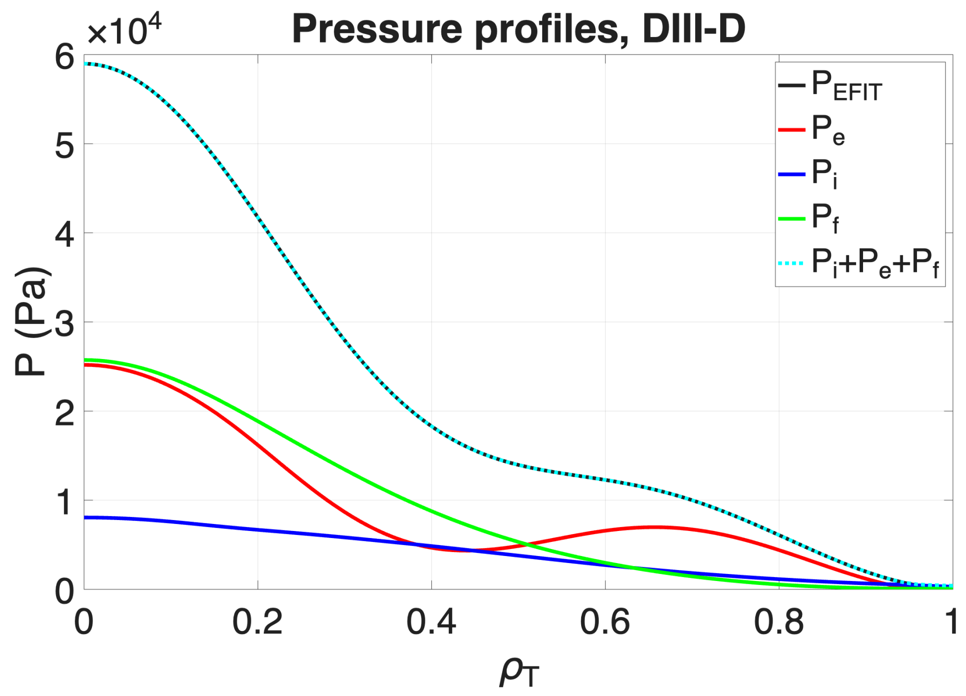


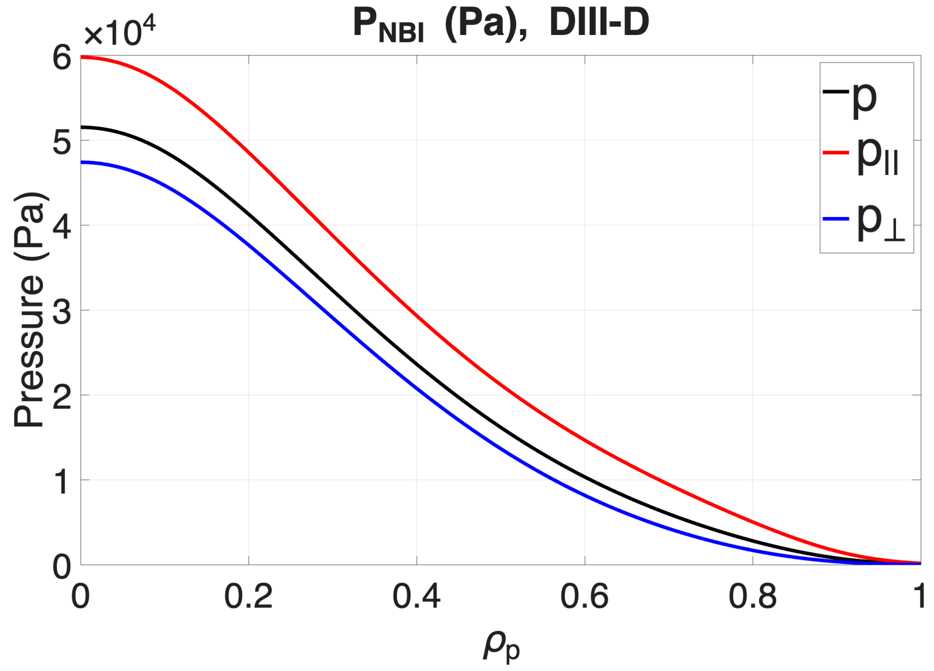


➢**Current balance** $\mathbf{J}_e(\psi,\theta) = \Sigma_k \mathbf{J}_k(\psi,\theta) - \nabla \times \mathbf{B}/\mu_0$ is imposed, as anisotropic EP current may be non-negligible

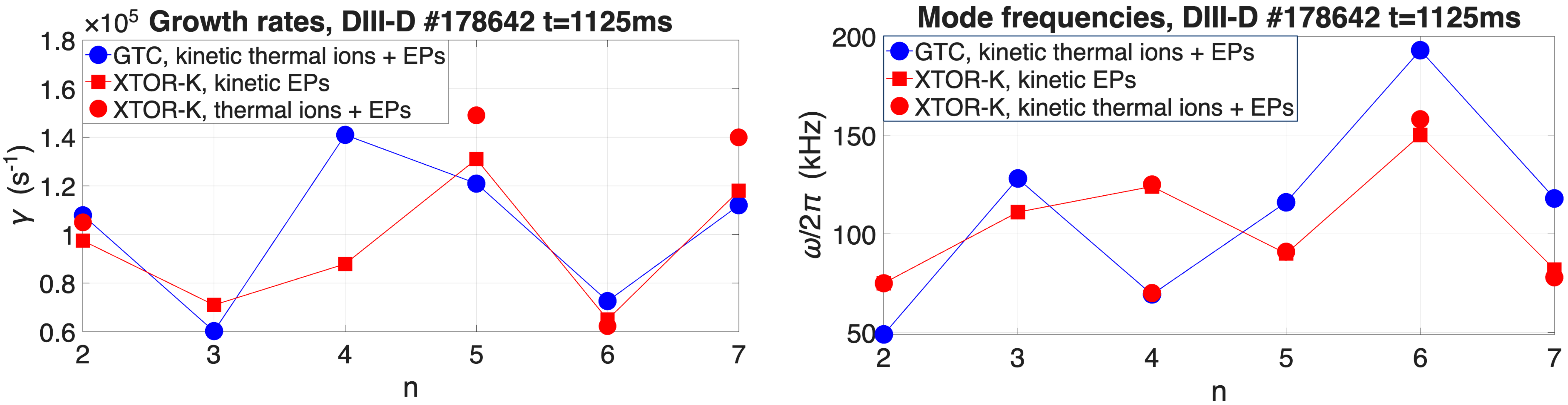
➢**Isotropic pressure balance** $T_e = (P_{MHD} - \Sigma_k P_k)/n_e$ is enforced, not accounting for the EP anisotropy.

➢The isotropy **approximation** is not **too stringent** for **moderate anisotropy** as in **NBI-heated DIII-D plasmas**





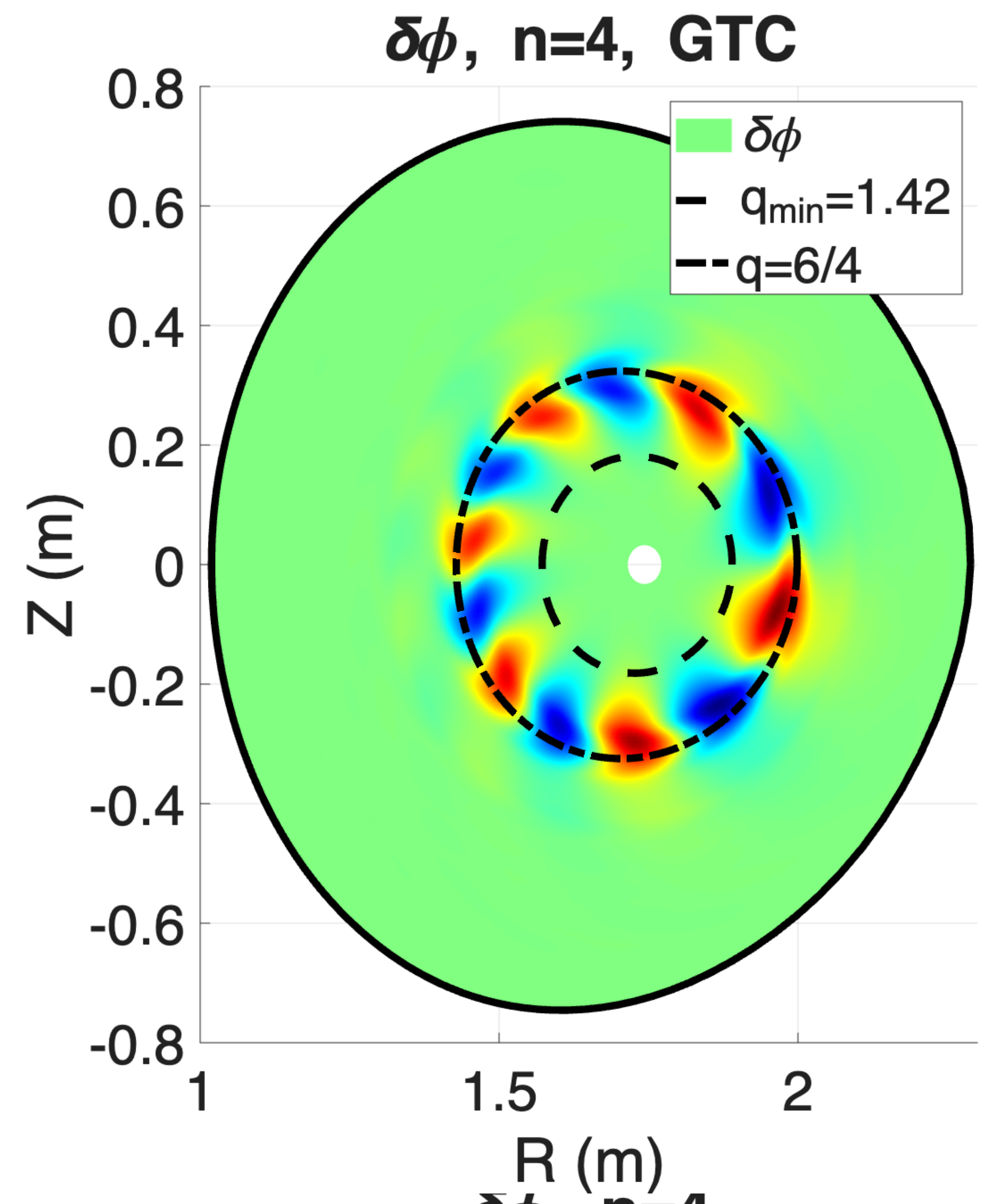
Linear stability across toroidal mode numbers

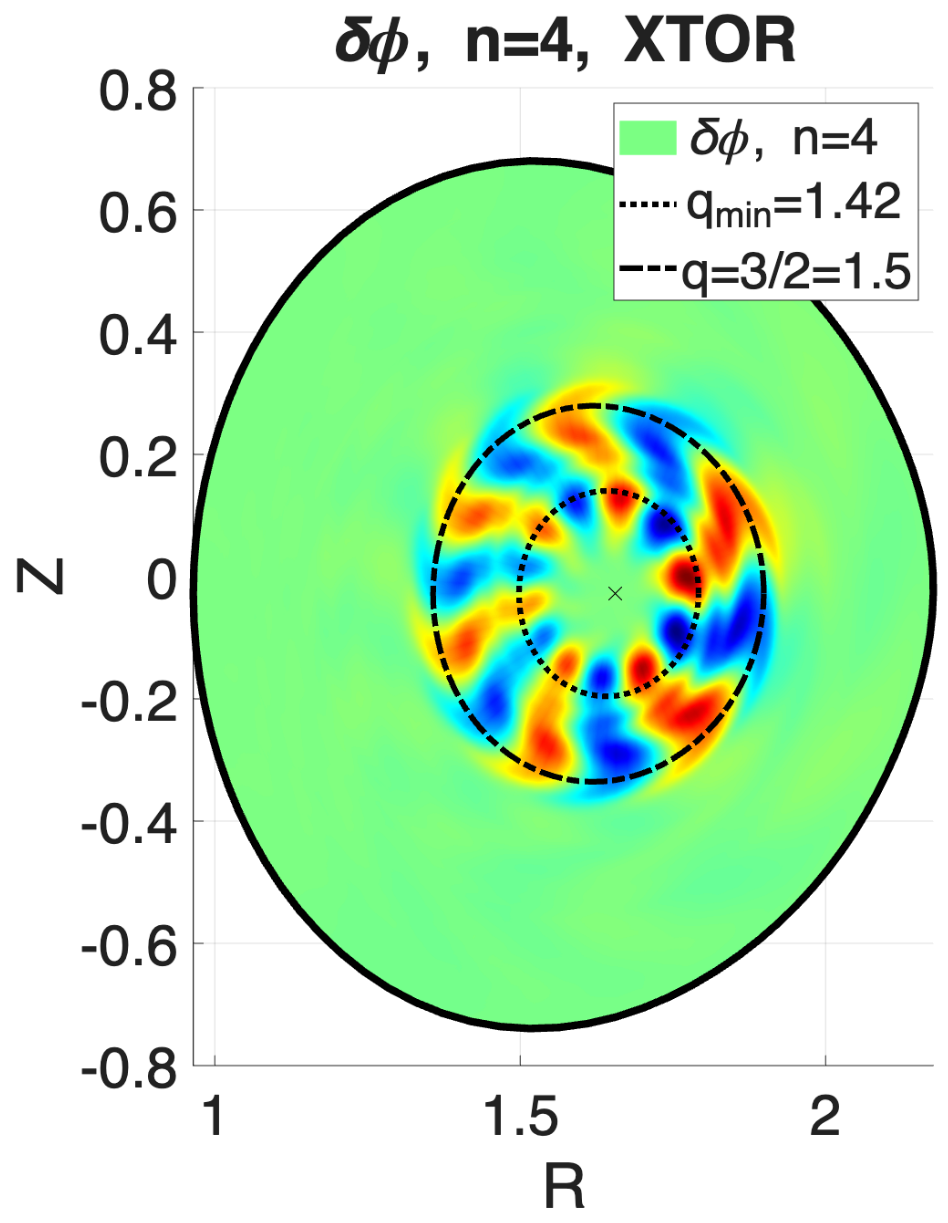


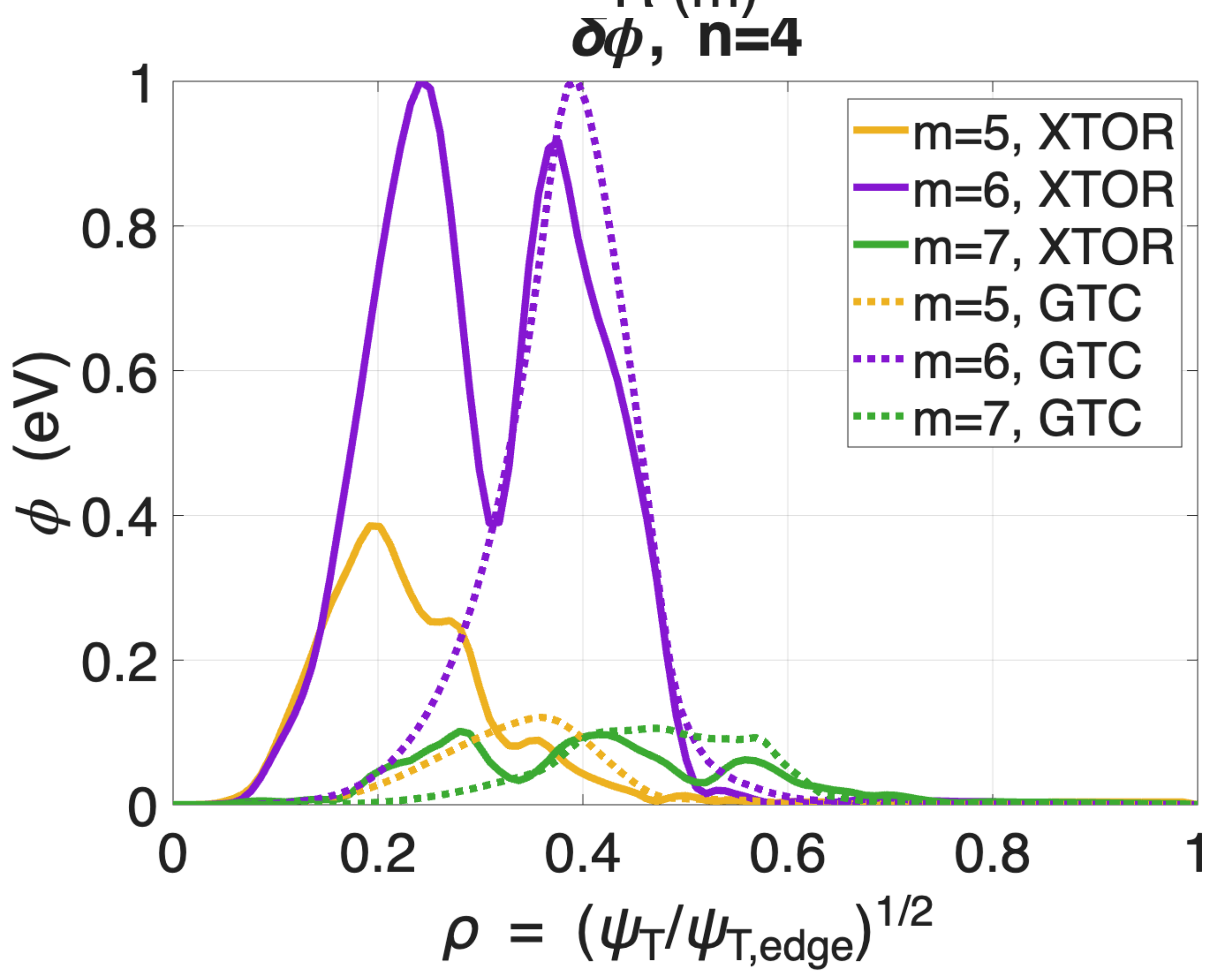
- ➢**XTOR multi-n** simulations with **kinetic EPs** and **kinetic thermal ions+EPs** are compared to **GTC** δF simulations **at t=1125ms**
- ➢Kinetic thermal ions impact on **RSAE/TAE found weak**, but they **destabilise the n=4 BAE [1]**
- ➢Overall a **reasonable agreement is achieved,** despite **importance differences** for the **n=4 BAE growth rate**
- ➢q_{min} **scan required** to compare **more precisely BAE stability** between **XTOR** and **GTC**

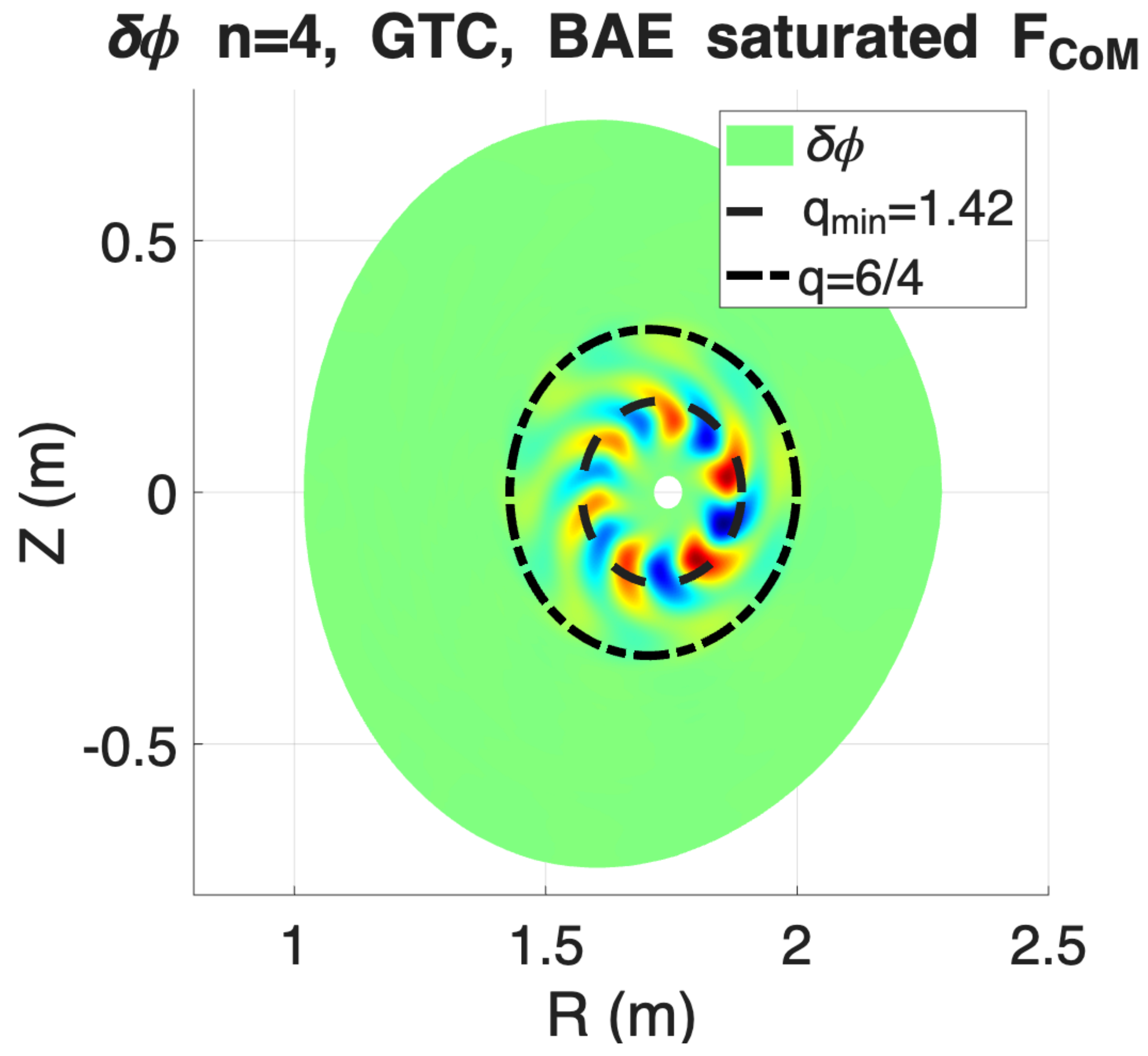
[1] L. Qi et al., Phys. Plasmas (2013)

Linear stability of the n=4 mode



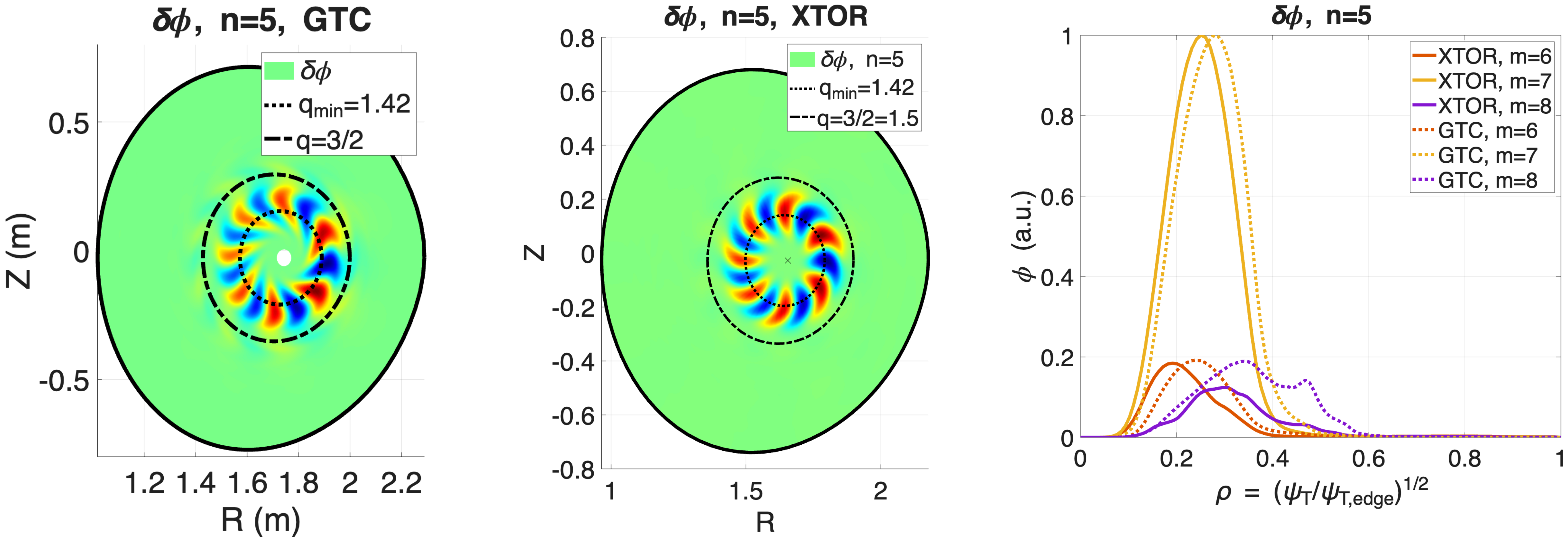






- For both GTC and XTOR, **n=4 RSAE** and **BAE co-exist** (both with **dominant m=6**)
- In **XTOR,** the **BAE** and **RSAE** have **similar growth rates,** while in **GTC** the **BAE largely dominates**
- The **BAE mode structure** is found **similar** between **XTOR** and **GTC**
- In **GTC**, if the simulation is **restarted** with the **CoM pdf after BAE saturation**, the RSAE **appears clearly** as in XTOR

Linear stability of the n=5 mode

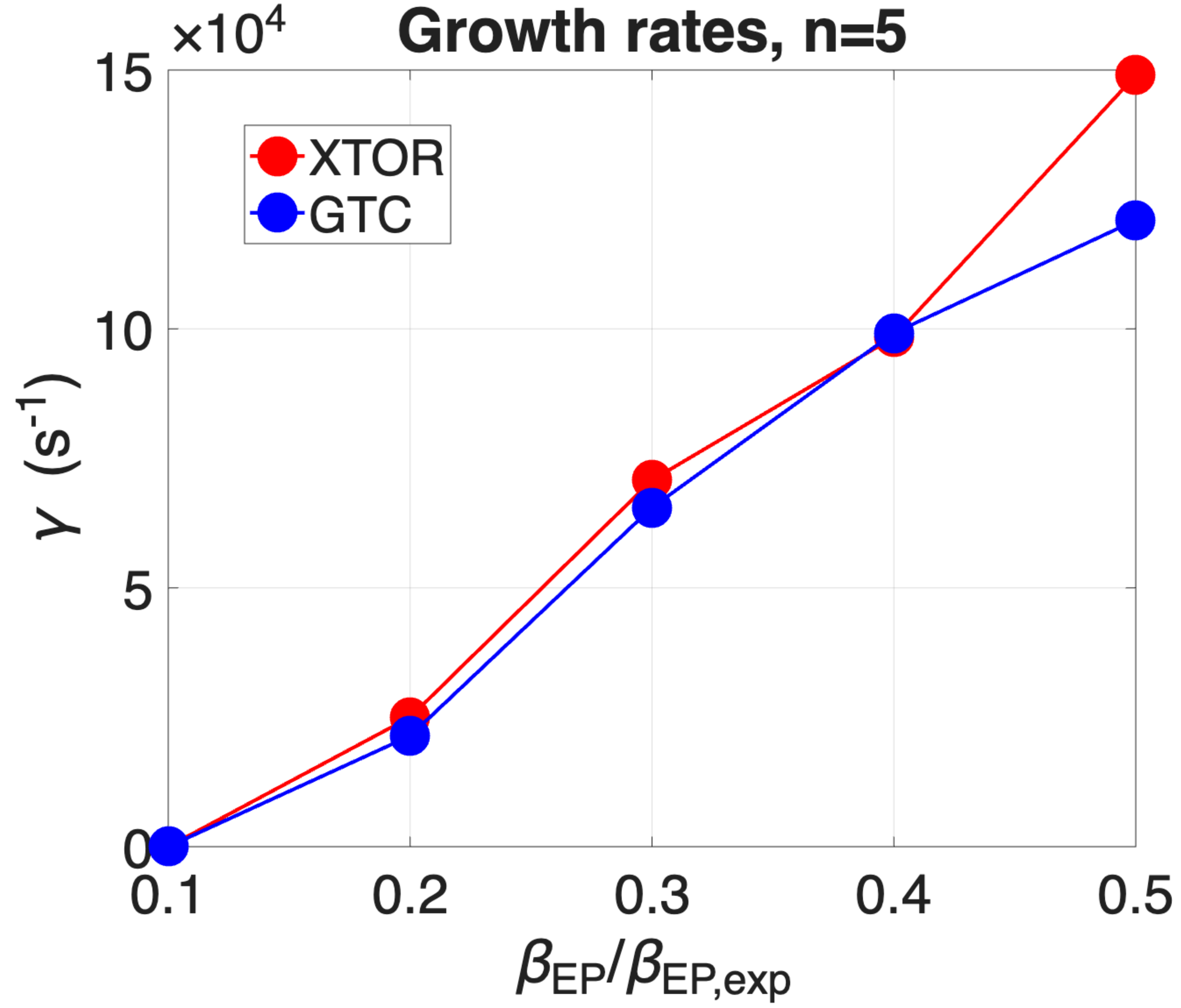


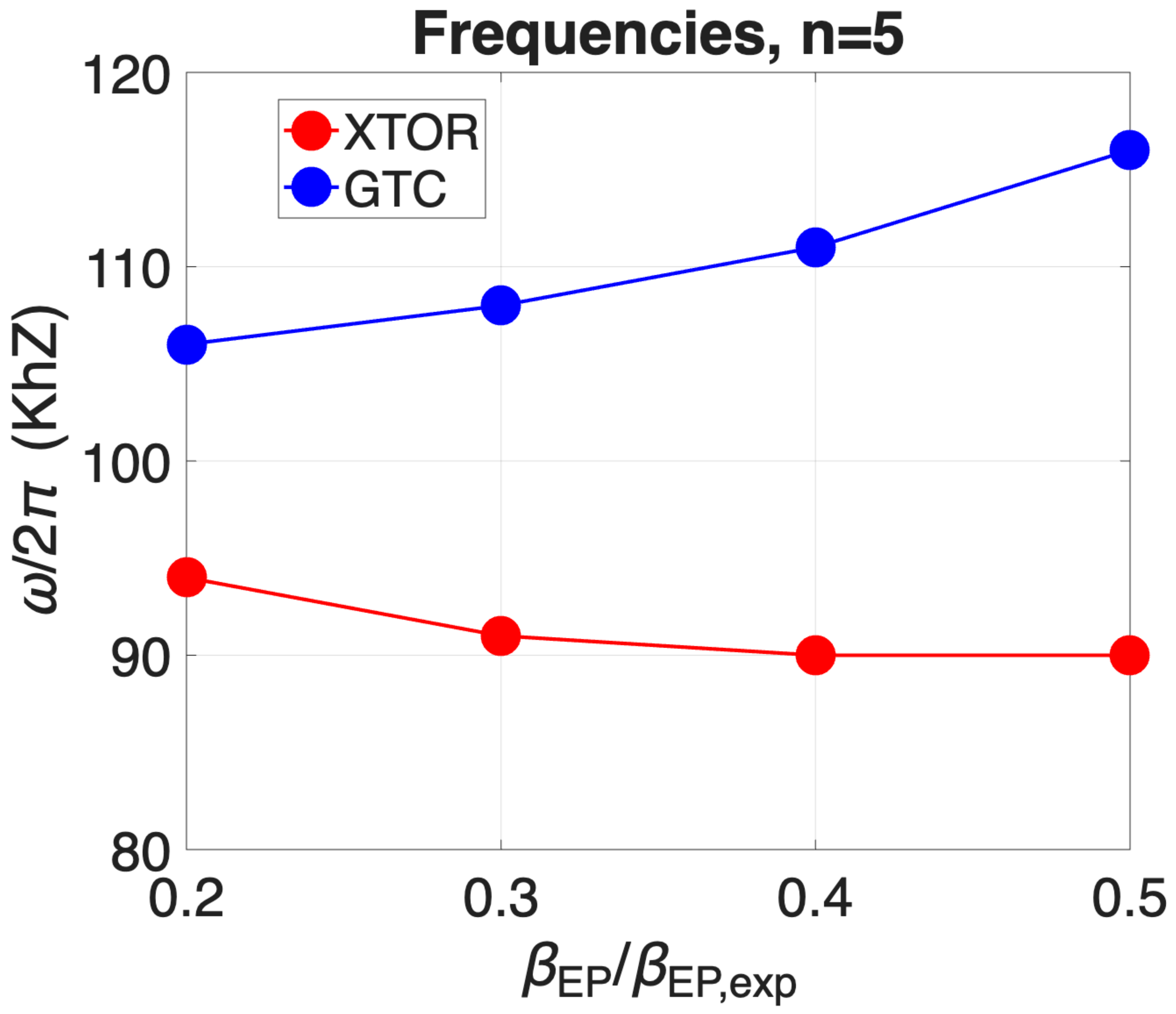
➢For the **main unstable mode in XTOR** (n=5 RSAE) a **good agreement** is obtained for the **mode structure**

➢The **tilting** of the structure seems **more significant in GTC ->** differences in **zonal shear** or **m=8 harmonic ?**

➢For now instead of the n=4, the **n=5 mode is used** to performed a β_{EP} **scan** on **linear stability**

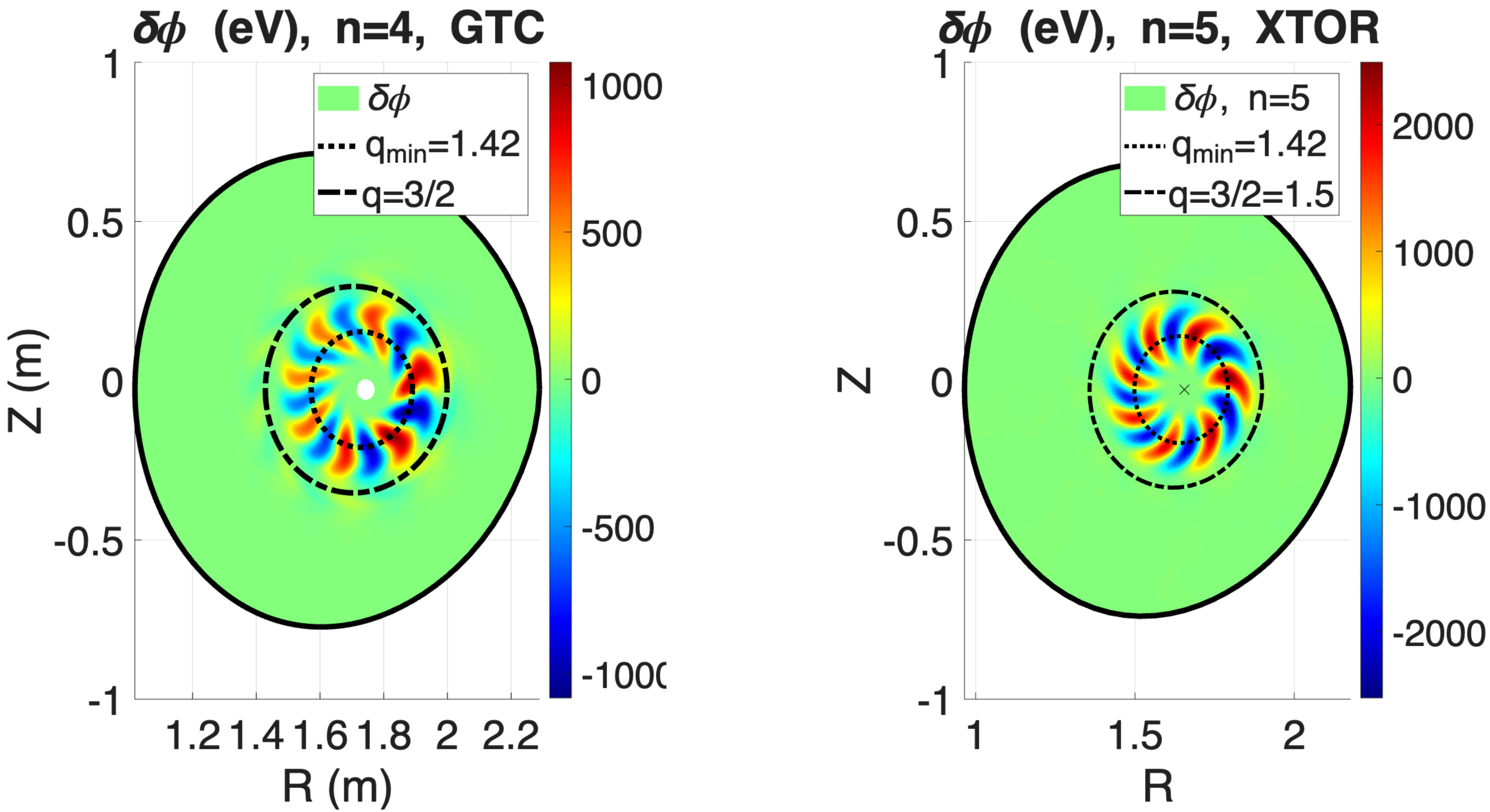
β_{EP} scan on n=5 mode





- For the **n=5 RSAE,** there is a **good agreemen**t for the **linear stability** between **GTC** and **XTOR**
- **Not as good** agreement for the **mode frequencies**, **XTOR** frequencies are **consistently 20-30 kHz lower**
- For $\beta_{EP}/\beta_{EP,exp} = 0.5$, for **both codes**, an **equivalent Maxwellian** yields $\gamma = 6 \times 10^4 s^{-1}$ (about **2 times lower**)

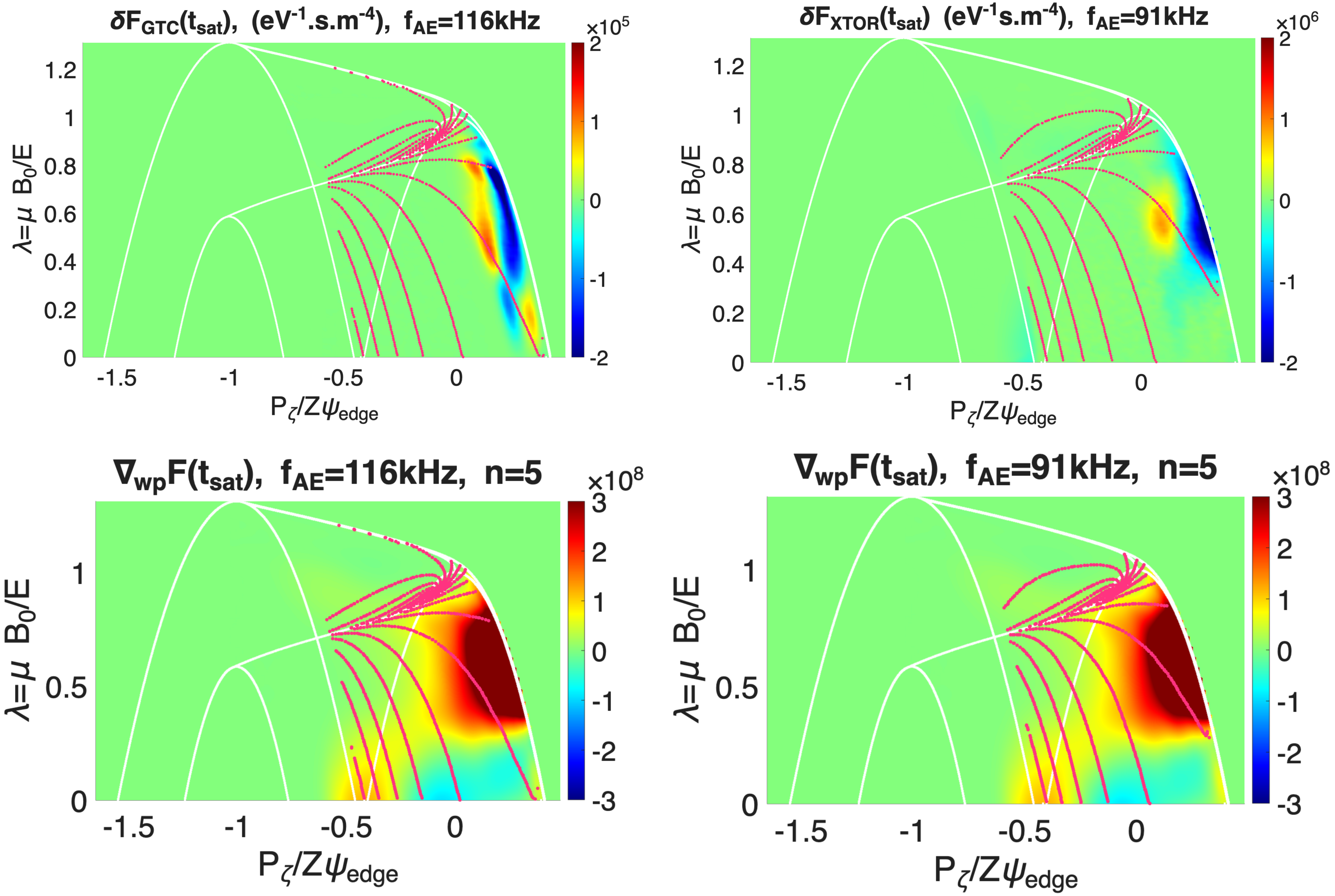
Nonlinear saturation of n=5, $\delta\phi$ amplitude



➢The n=5 mode saturates at an **amplitude 2.5 higher** in **XTOR** simulations compared to **GTC**

➢Saturation amplitudes to be **compared with ECE measurements** (probably too large here)

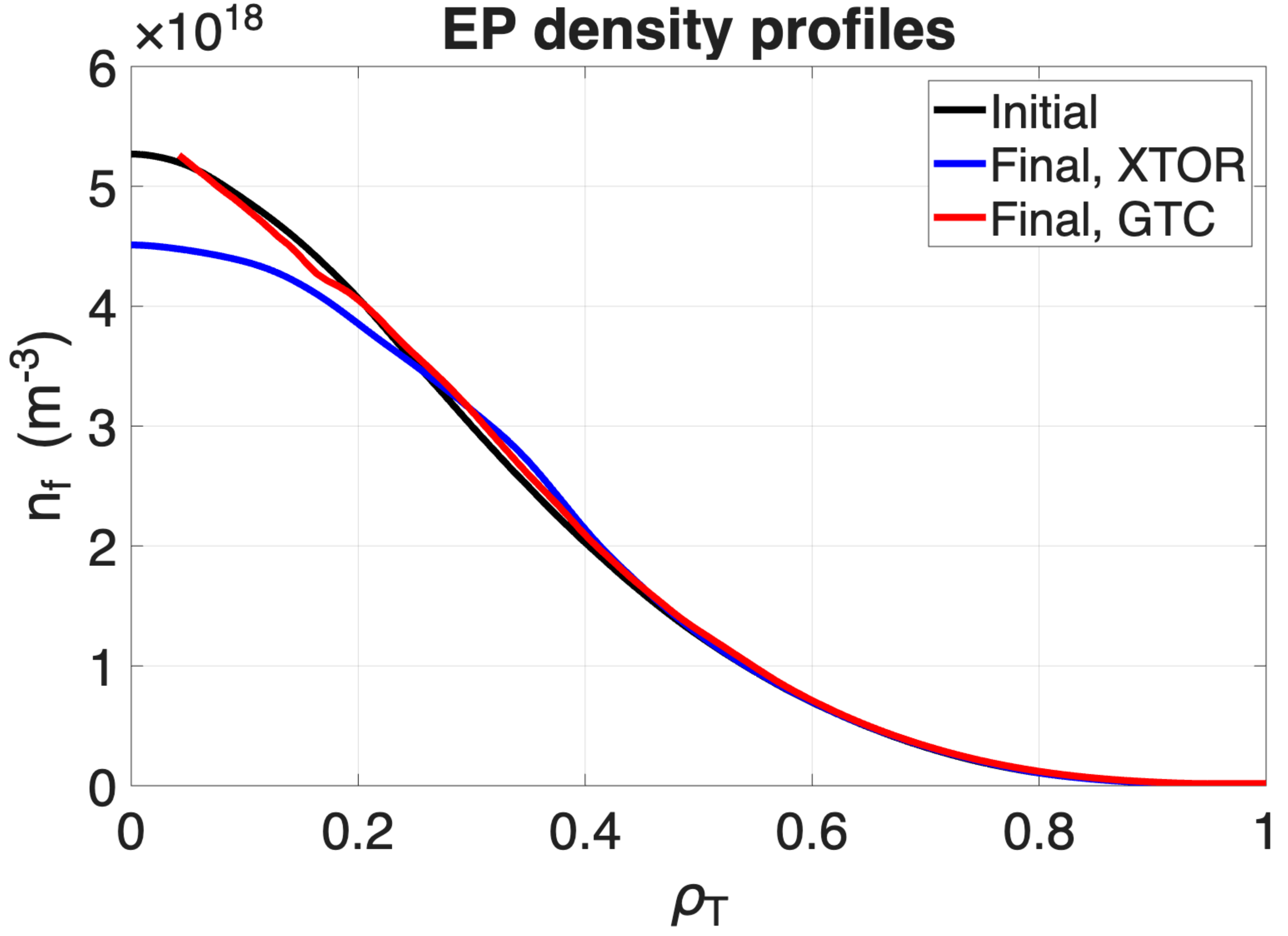
Nonlinear saturation of n=5, PSZS



- ➢The difference in **frequency** by 20 kHz leads to **shifted wave-particle resonance** locations
- ➢The **inward/outward EP transport** matches the **sign** of the **EP drive** $\nabla_{wp}F_0 = n\partial_{P_\varphi}F_0 + \omega\partial_E F_0$
- ➢In XTOR, the **frequency shift prevents** the main resonance to **explore** the $\nabla_{wp}F_0 < 0$ **zone**
- ➢Overall, the **nonlinear transport is 10 times stronger in XTOR**

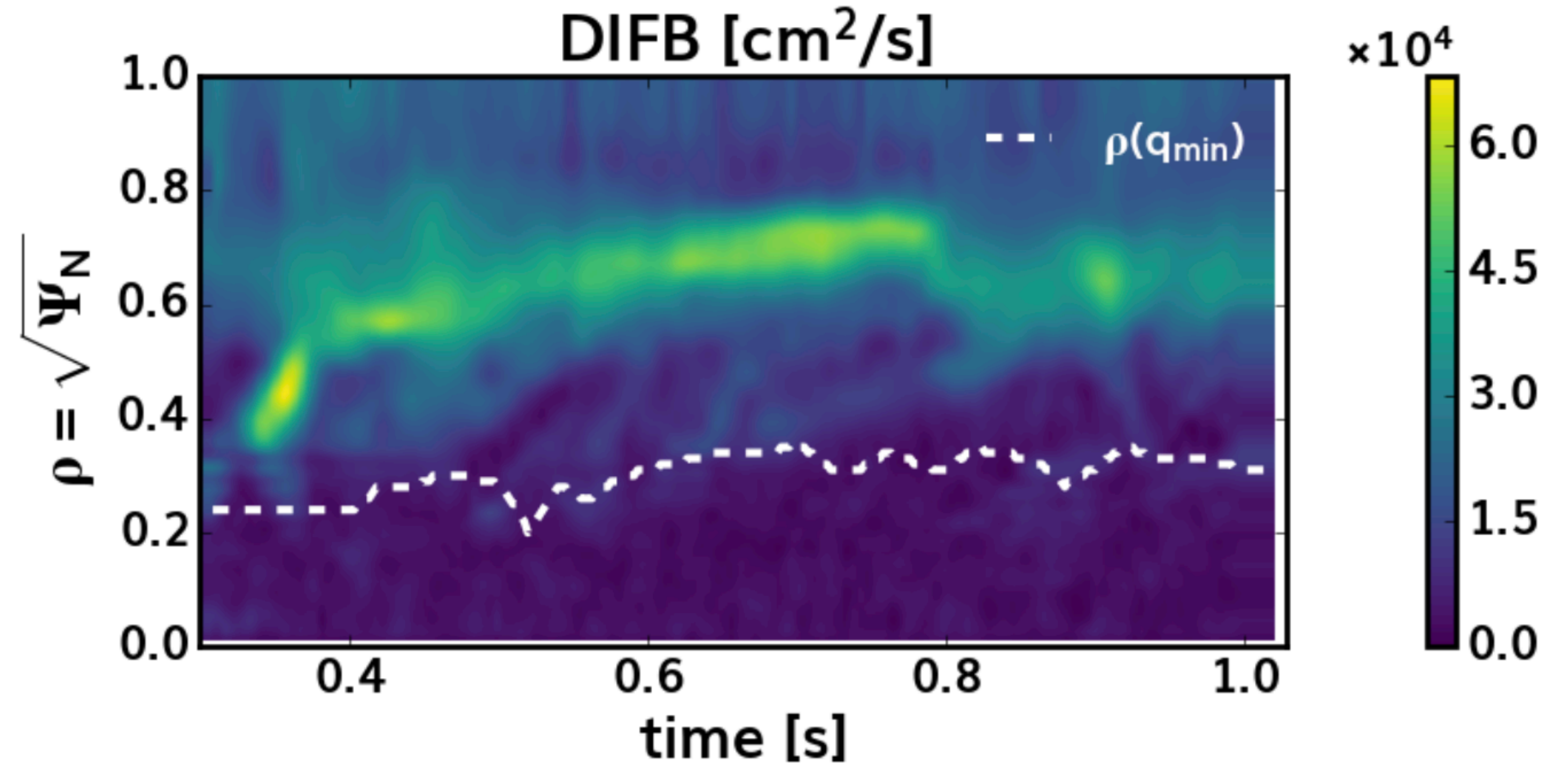
  → to investigate (multi-n simulation for XTOR)

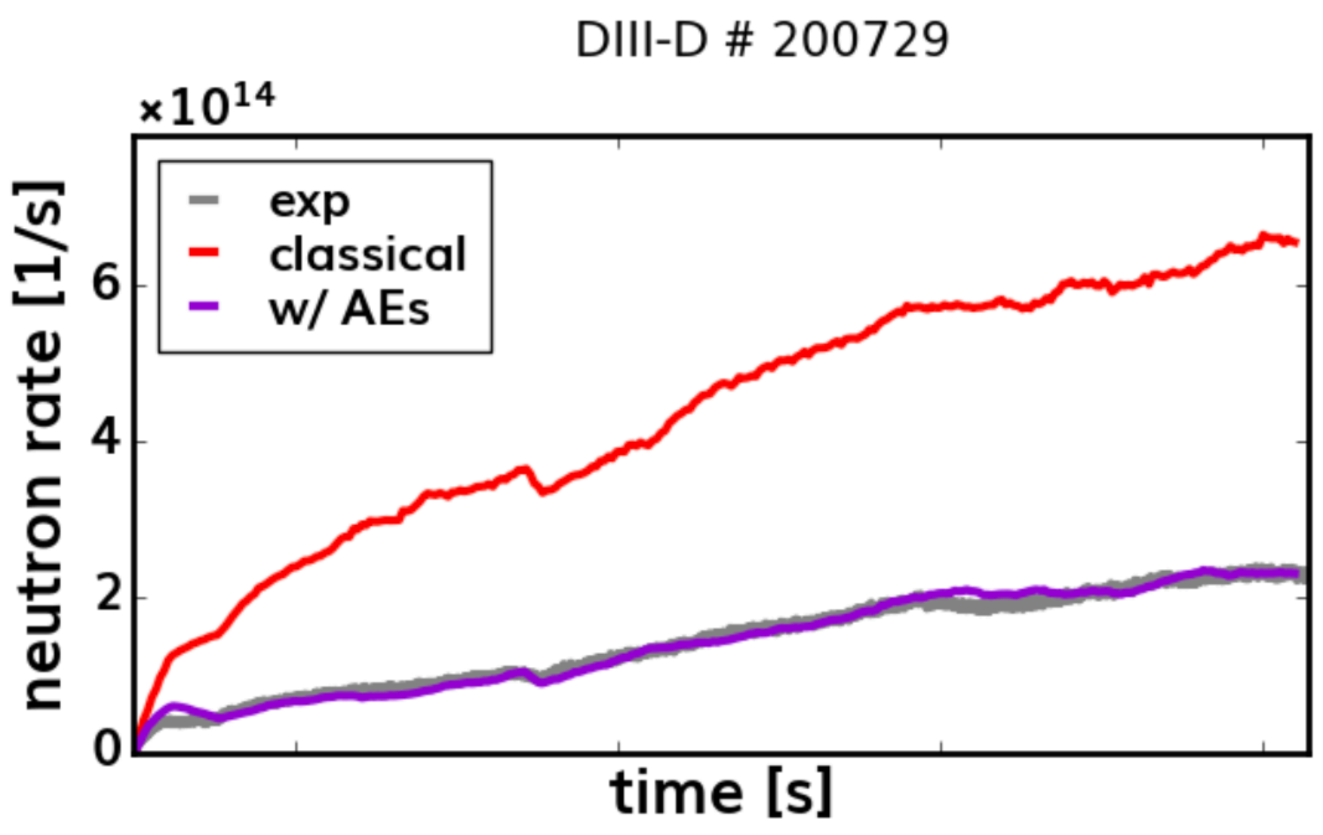
Nonlinear saturation of n=5, 1D EP transport

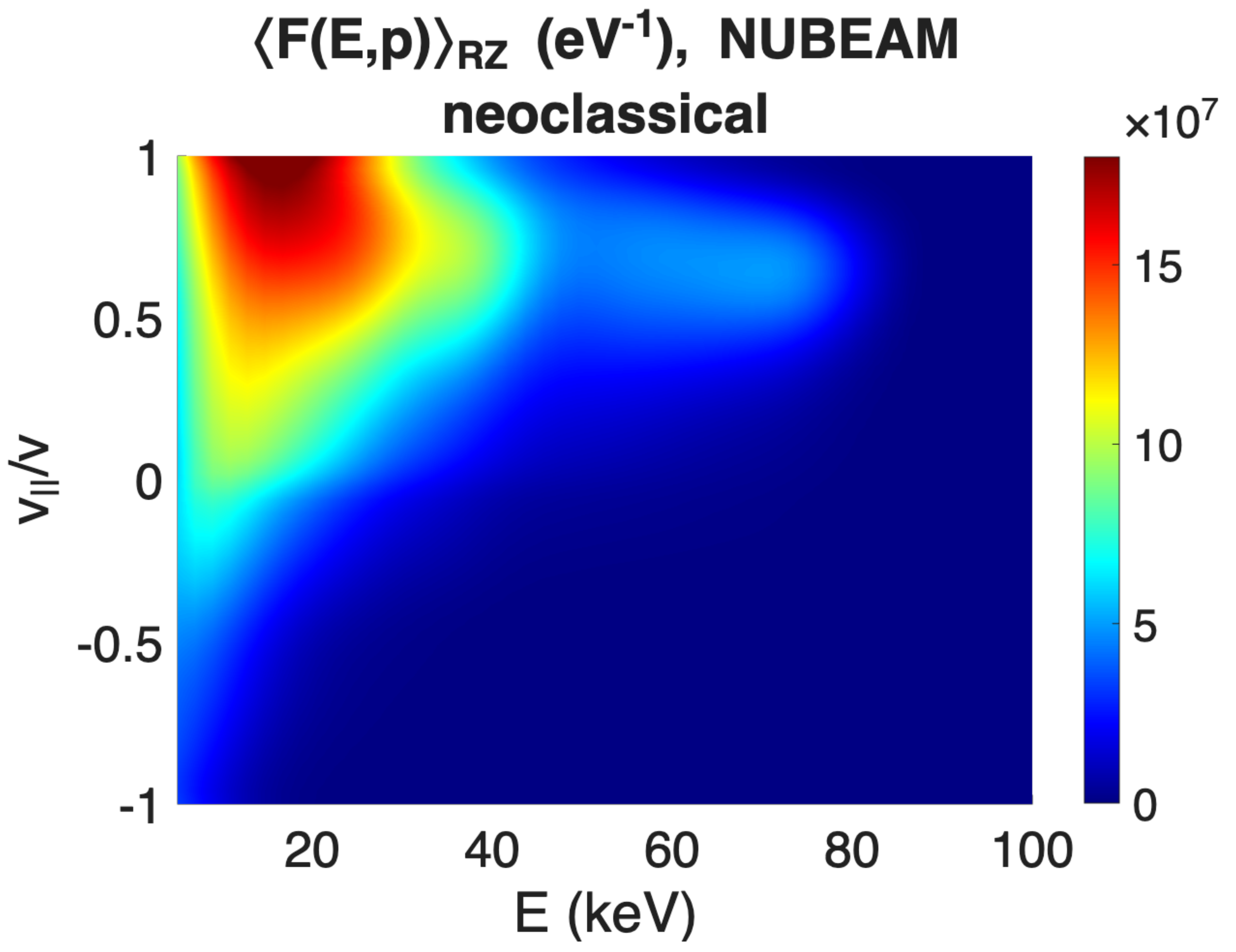


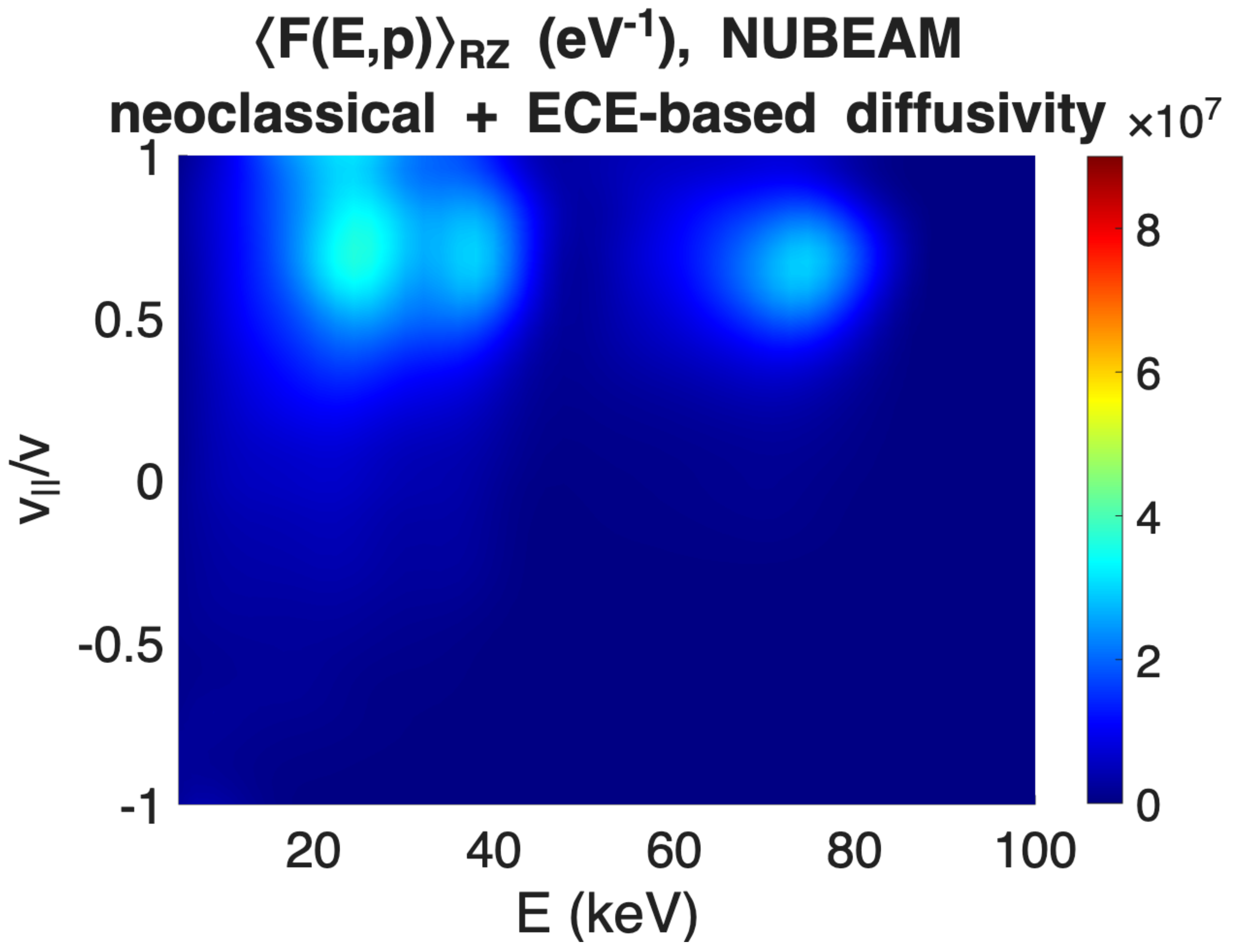
➢**EP flattening** much **more significant in XTOR simulations**, consistently with RSAE saturation amplitude and PSZS

More realistic beam reconstruction









- ➢A **new module** has been developed in TRANSP-NUBEAM (**K. Callahan**) to **account for EP transport** due to **instabilities**
- ➢**ECE** measurements of the **mode amplitudes** in (t, ψ_T) used to **infer a diffusivity profile** on NUBEAM markers
- ➢**Method applied successfully** on DIII-D discharge **#200729**, **match** between **predicted** and **experimental** neutron rate
- ➢The EP beam **significantly changes** in both **position** and **velocity** spaces
- ➢**XTOR simulations** will be performed on a **new NUBEAM input** for #178642, to **investigate changes** in **BAE stability**

Conclusions

➢**XTOR** has been **successfully interfaced** with **EPCoM** outputs, enforcing a **true kinetic-MHD equilibrium** for **quiet** (and physical) **start-up.**

➢Nonlinear **AE simulations** on the **new ITPA-EP benchmark case** performed with **XTOR**

➢**Multi-n simulations XTOR** and **GTC** are in **relatively good agreement**, to the **exception of the dominant n=4 BAE**, sensitive to kinetic thermal ion effects in XTOR $\rightarrow q_{min}$ **scan required**

➢**PSZS comparison** between **GTC** and **XTOR impacted** by **difference** in linear mode **frequencies**, but **consistent** with **CoM space EP drive**

➢**Experimental validation** for the **BAE stabilisation** under perpendicular beam injection **to be performed** with the **new NUBEAM run** incorporating **ECE-based diffusivity**