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Verification and validation of AE dynamics with realistic energetic particle distributions in DIII-D plasmas

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Why realistic EP distribution matters

➤ **EP modes stability and nonlinear dynamics** is very sensitive to EP phase space **distribution gradients**

➤ Their **stability** is naturally expressed in **CoM space** (P_ϕ, μ, E)

$$\omega I_R(\omega) = \delta W_{MHD} + \delta W_{EP}(\omega) \quad \delta W_{EP}(\omega) \propto \frac{n \partial_{P_\phi} F + \omega \partial_E F}{(\omega + p \omega_\theta - n \omega_\phi)}$$

→ lead to the **development** of the **EPCoM code [1]**, providing **transformation** between **representations**, from and **towards CoM space**

➤ **EP instabilities** can **quench turbulent transport** [2-5], therefore **realistic EP drive is key** [6] in predicting the **beneficial operation domain** in current and future tokamaks

➤ 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.*

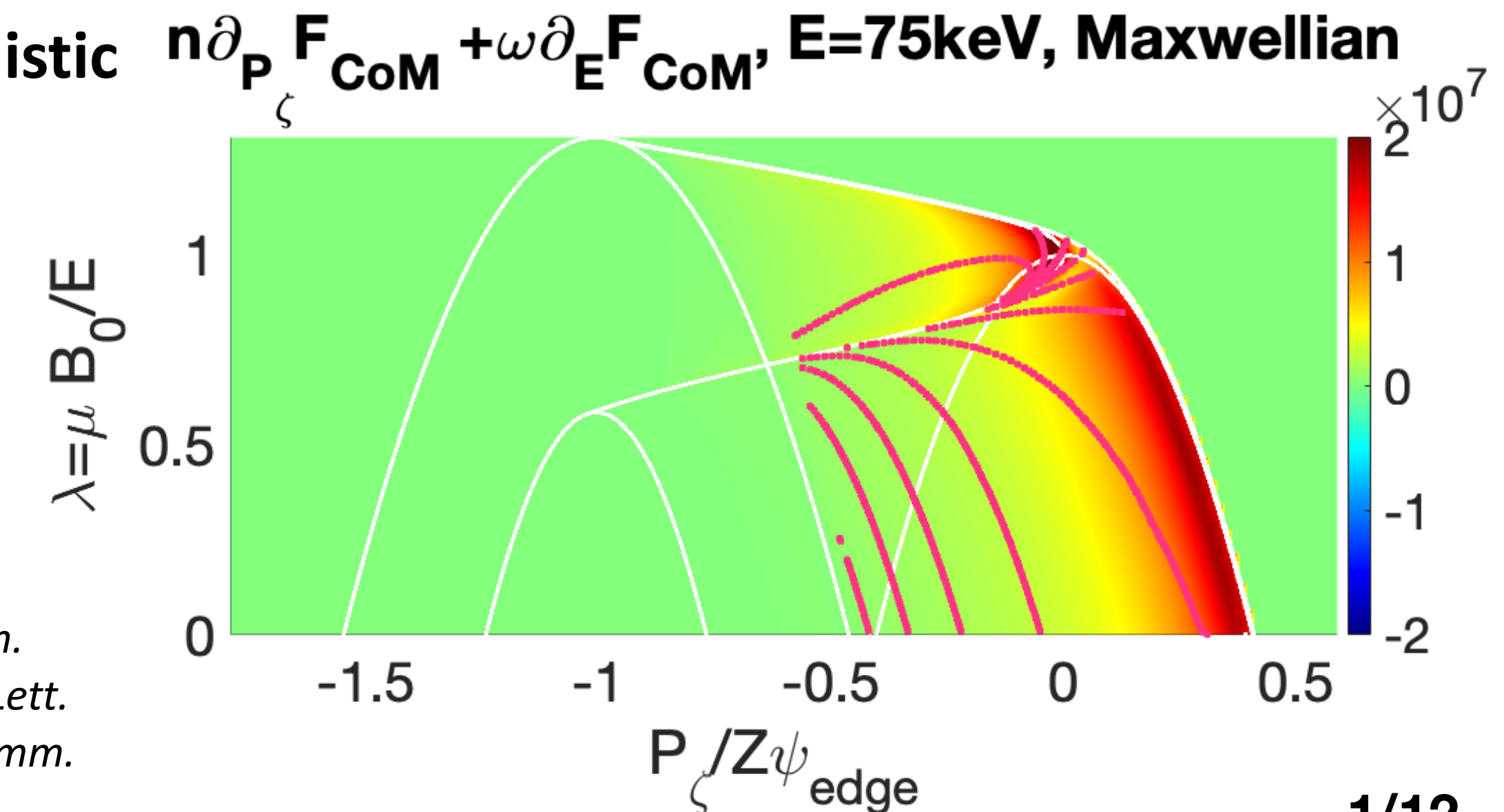
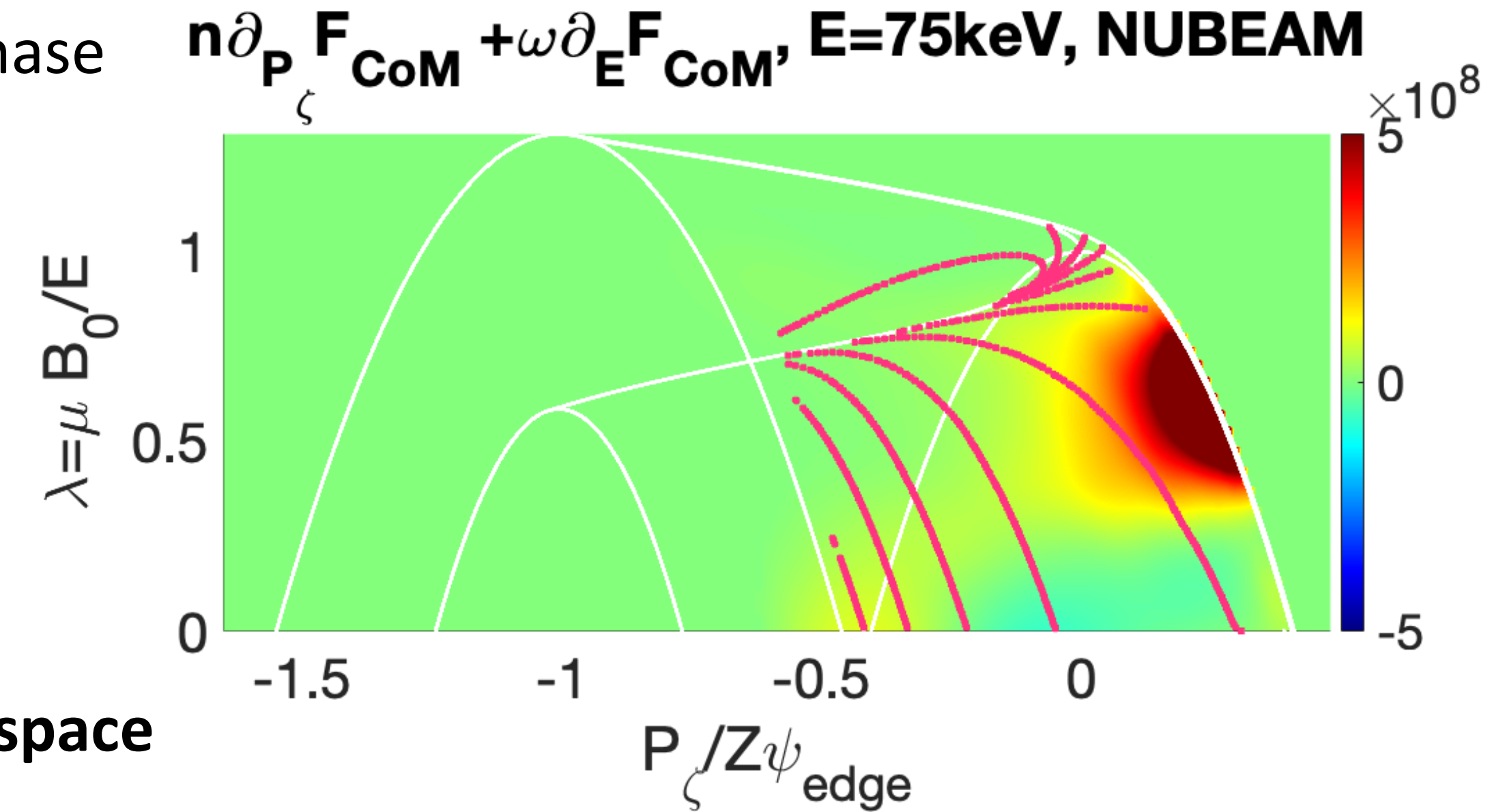
[2] S. Mazzi et al. 2022, *Nat. Phys.*

[3] G. Brochard et al. 2024, *Phys. Rev. Lett.*

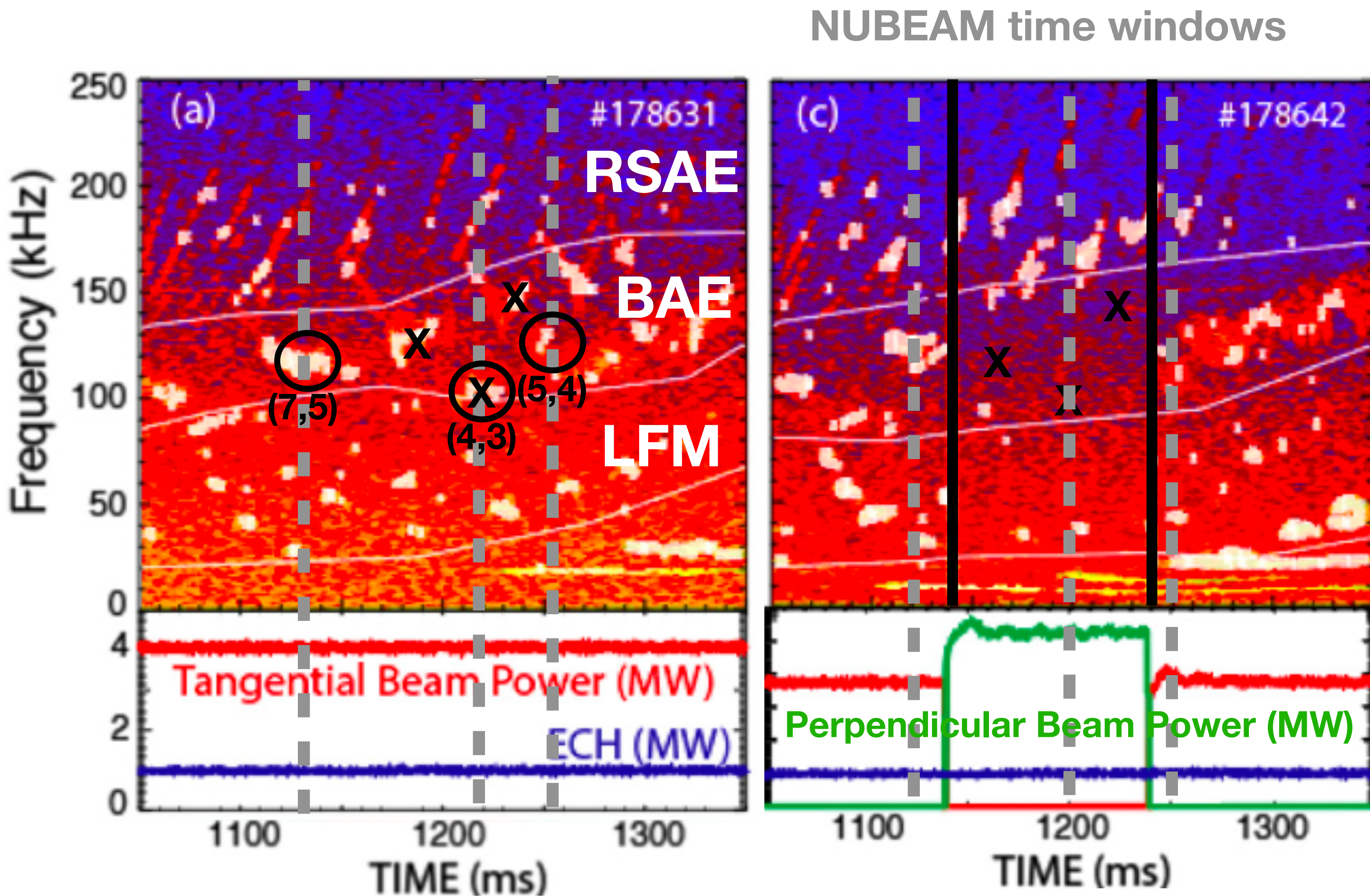
[4] J. Garcia et al. 2024, *Nat. Comm.*

[5] X. D. Du et al. 2025, *Phys. Rev. Lett.*

[6] A. Ishizawa et al. 2025, *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 **new ITPA-EP cross-code V&V** with **realistic EP distributions**

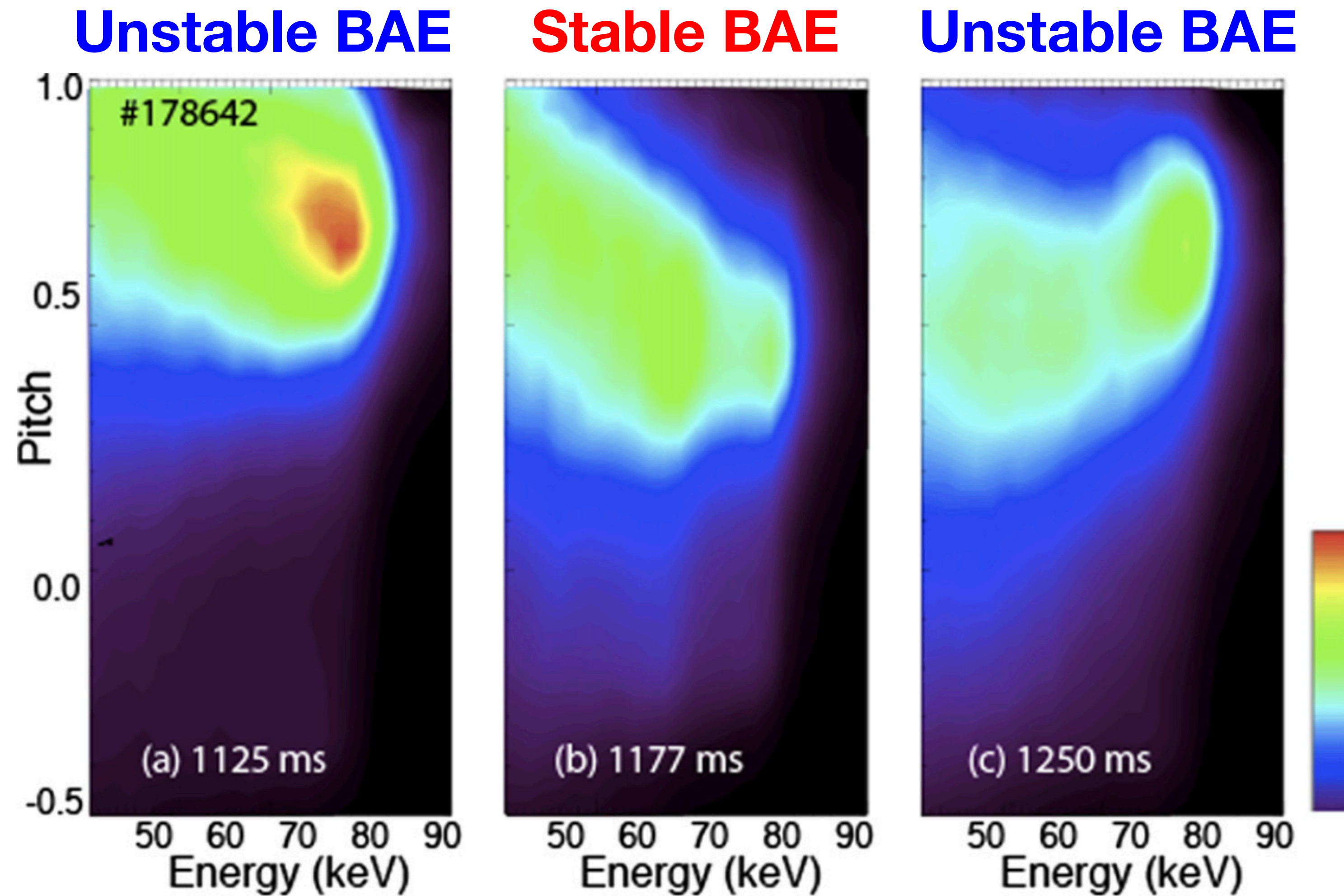
➤ In #178642, **tangential** beams briefly swapped by **perpendicular** ones, providing a stable window for BAEs

➤ 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**

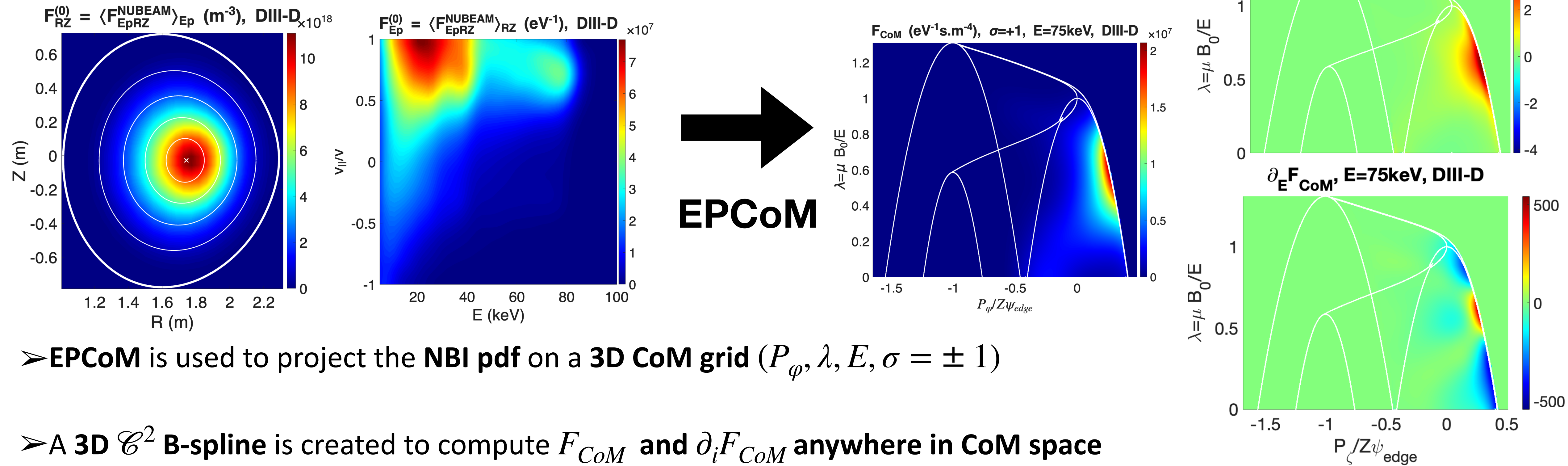
➤ Four **gyrokinetic** (GTC, ORB5, LIGKA, GENE) and five **kinetic-MHD** (XTOR-K, M3D-C1, M3D-K, MEGA, JOEREK) codes currently participate to this **benchmark activity**

Change in BAE stability due to high-energy EP ?



- BAEs become almost **immediately stable** at **beam substitution**, while $\tau_{SD} = 150ms > \tau_{swap} = 100ms$
- Changes in **high energy EPs** content could explain **change in BAE stability** [1]
- **NUBEAM** simulations do show a **modification of EP distribution** at injection energy $E_0 \sim 75keV$ [1]
- **GTC** and **XTOR** confirms that the **wave-particle energy exchange** is **maximal** at $E \sim 75keV$

Uniform EP input for all codes



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

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

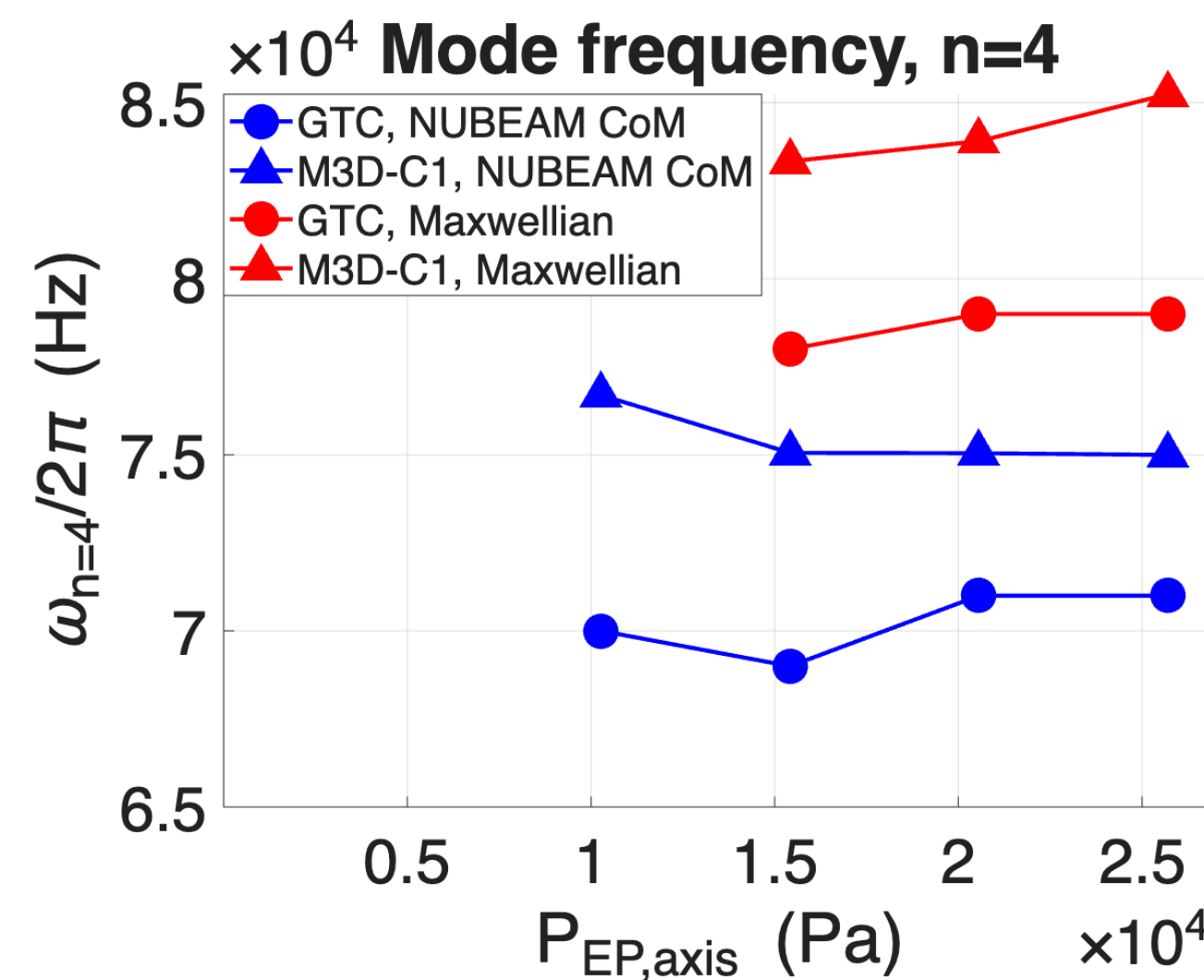
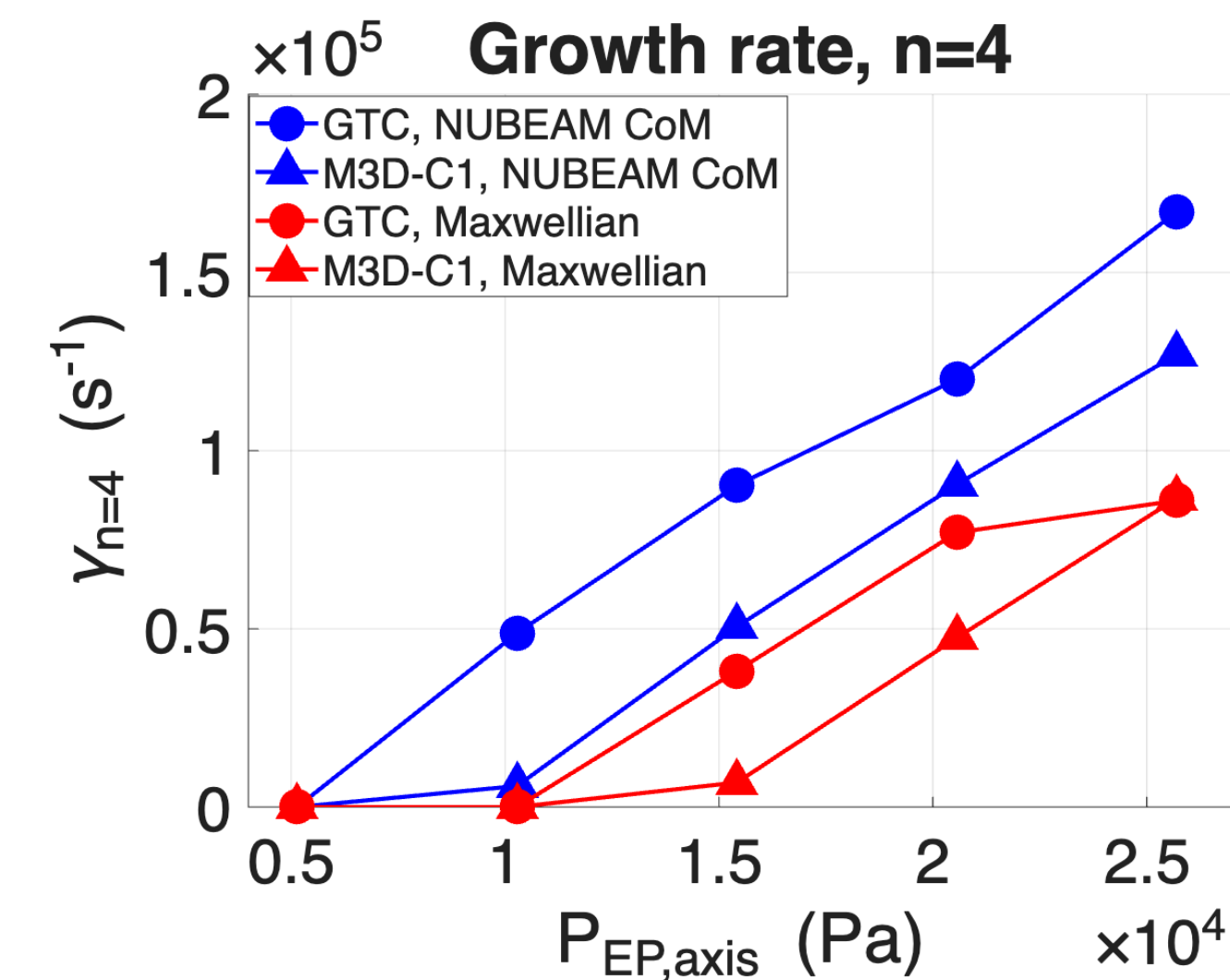
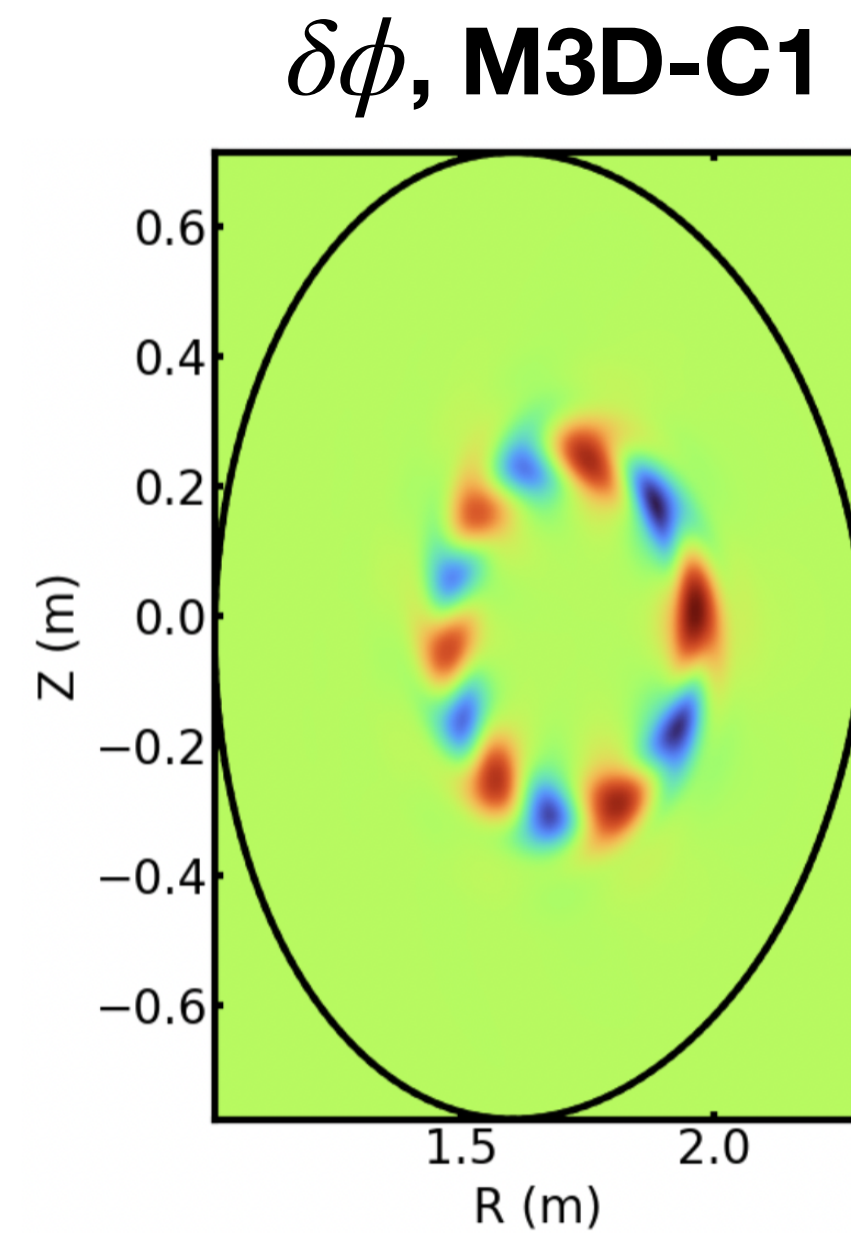
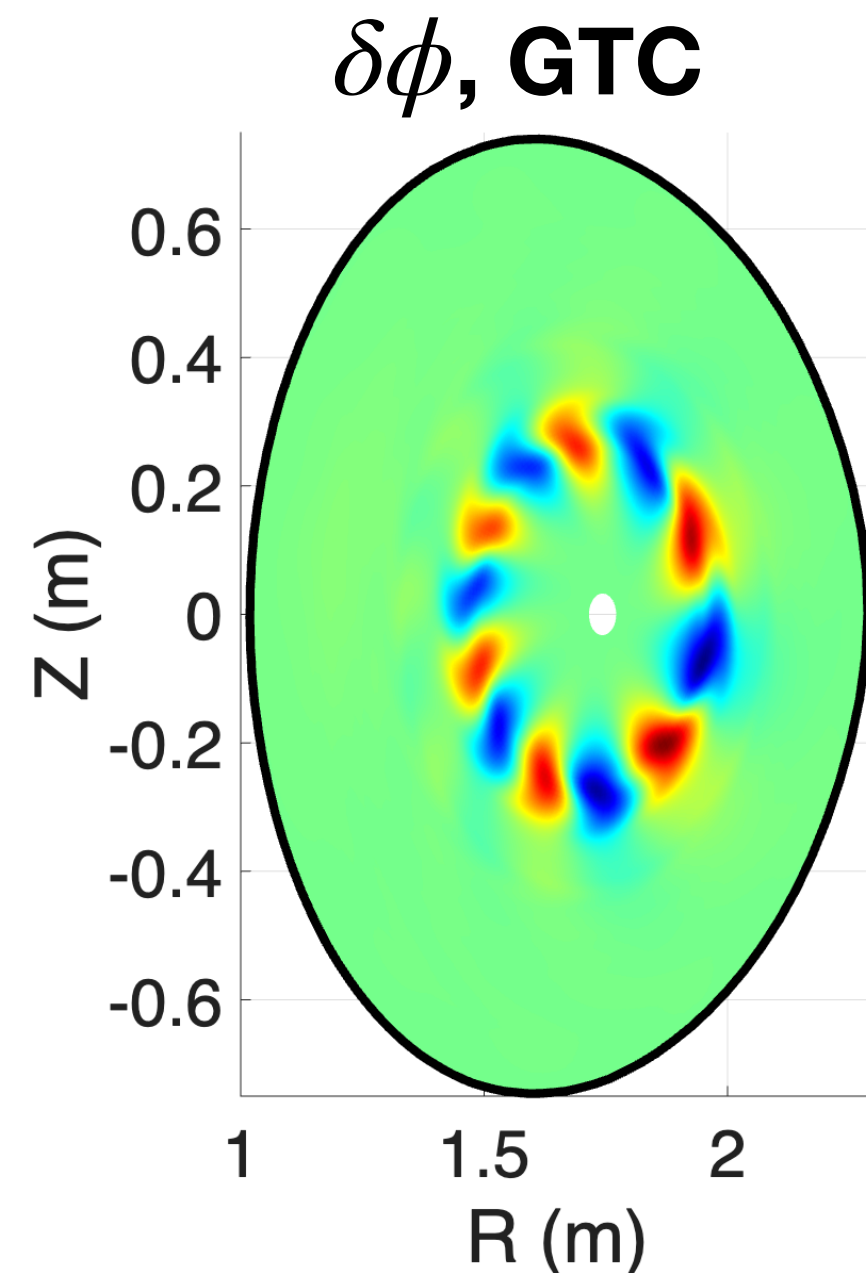
➤ **Full-F codes** using **Eulerian/semi-Lagrangian methods** can **directly** read F_{CoM} for **grid initialisation**, while a **Monte-Carlo approach** is required to load marker for **PIC codes**

➤ 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 :

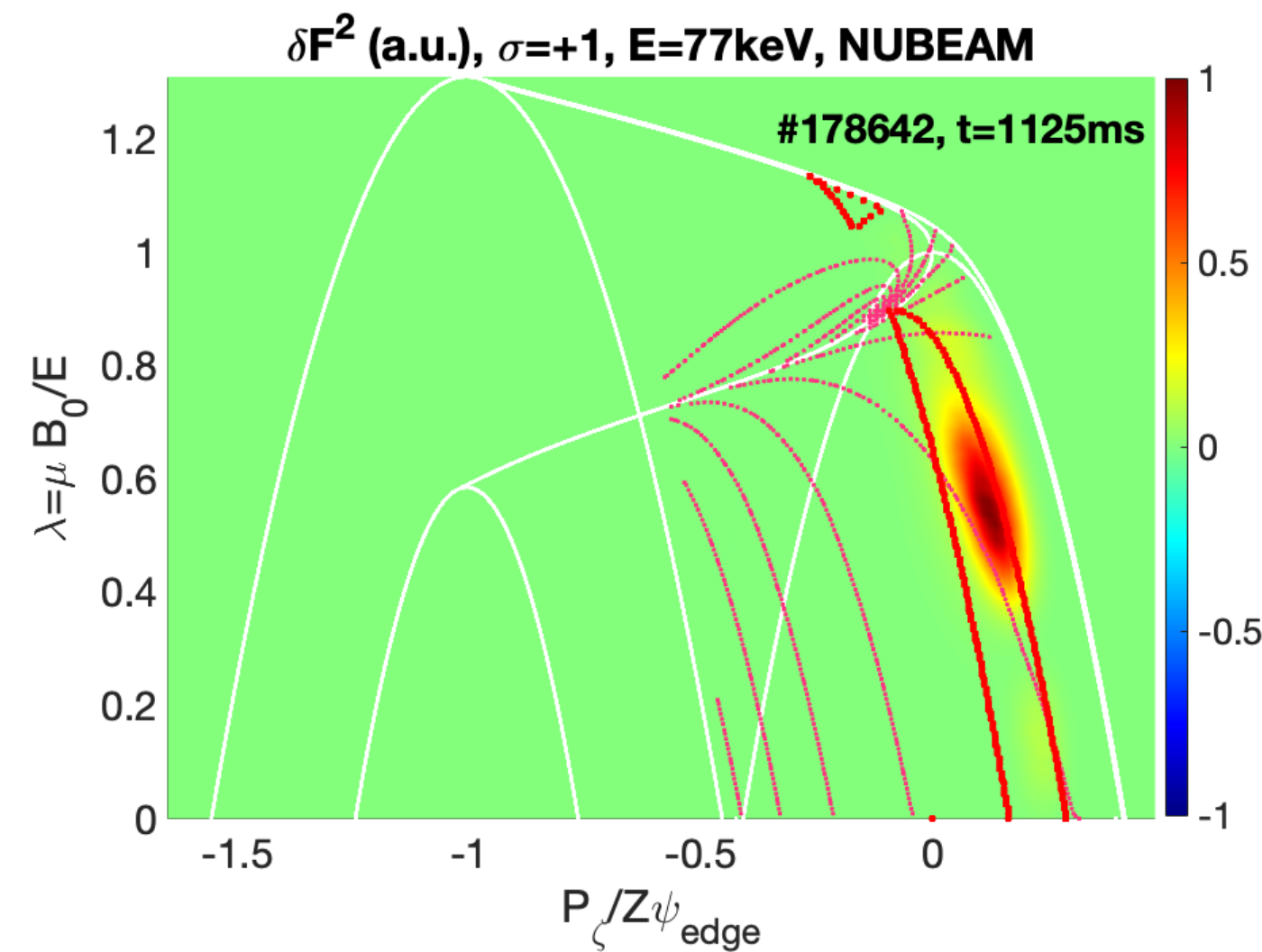
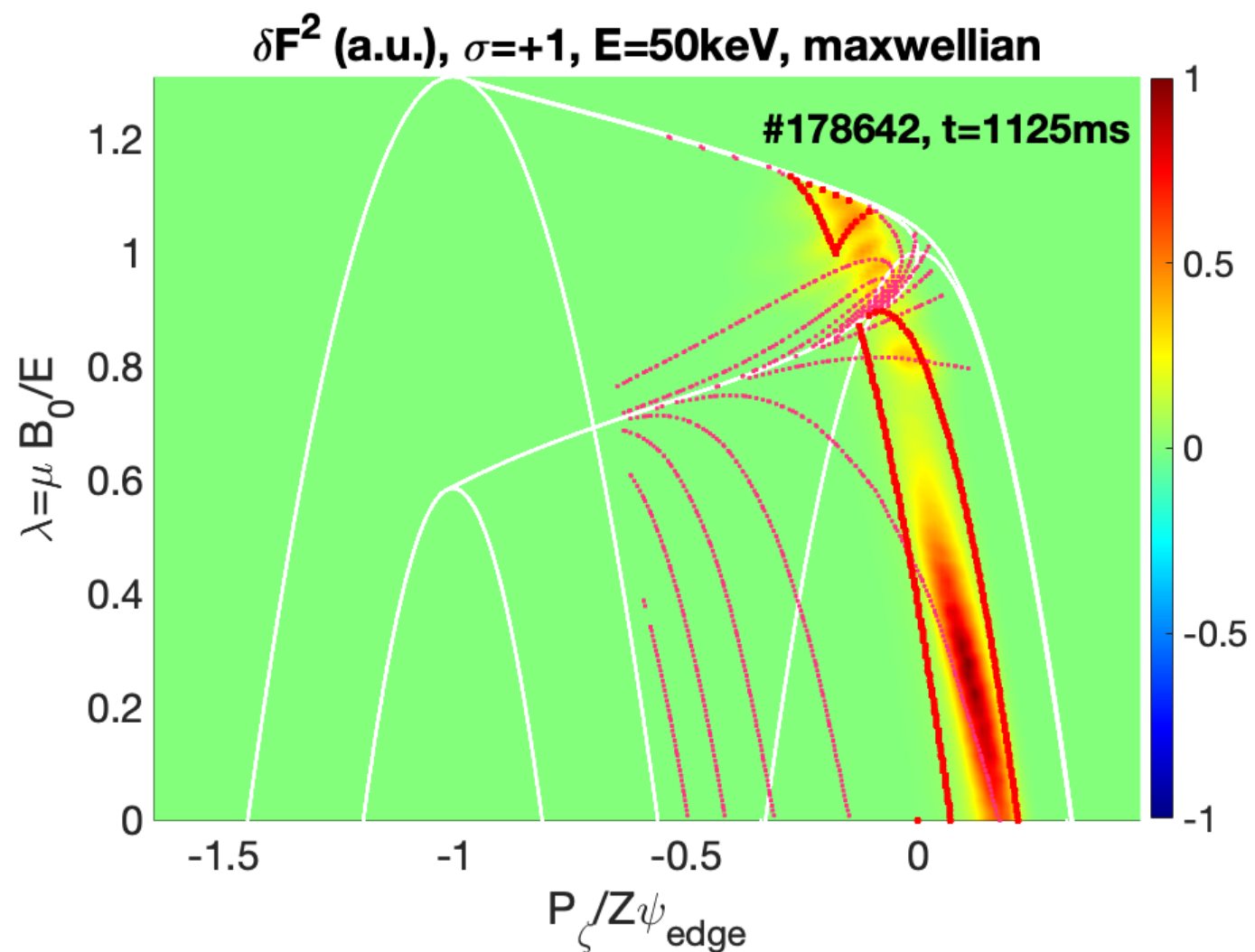
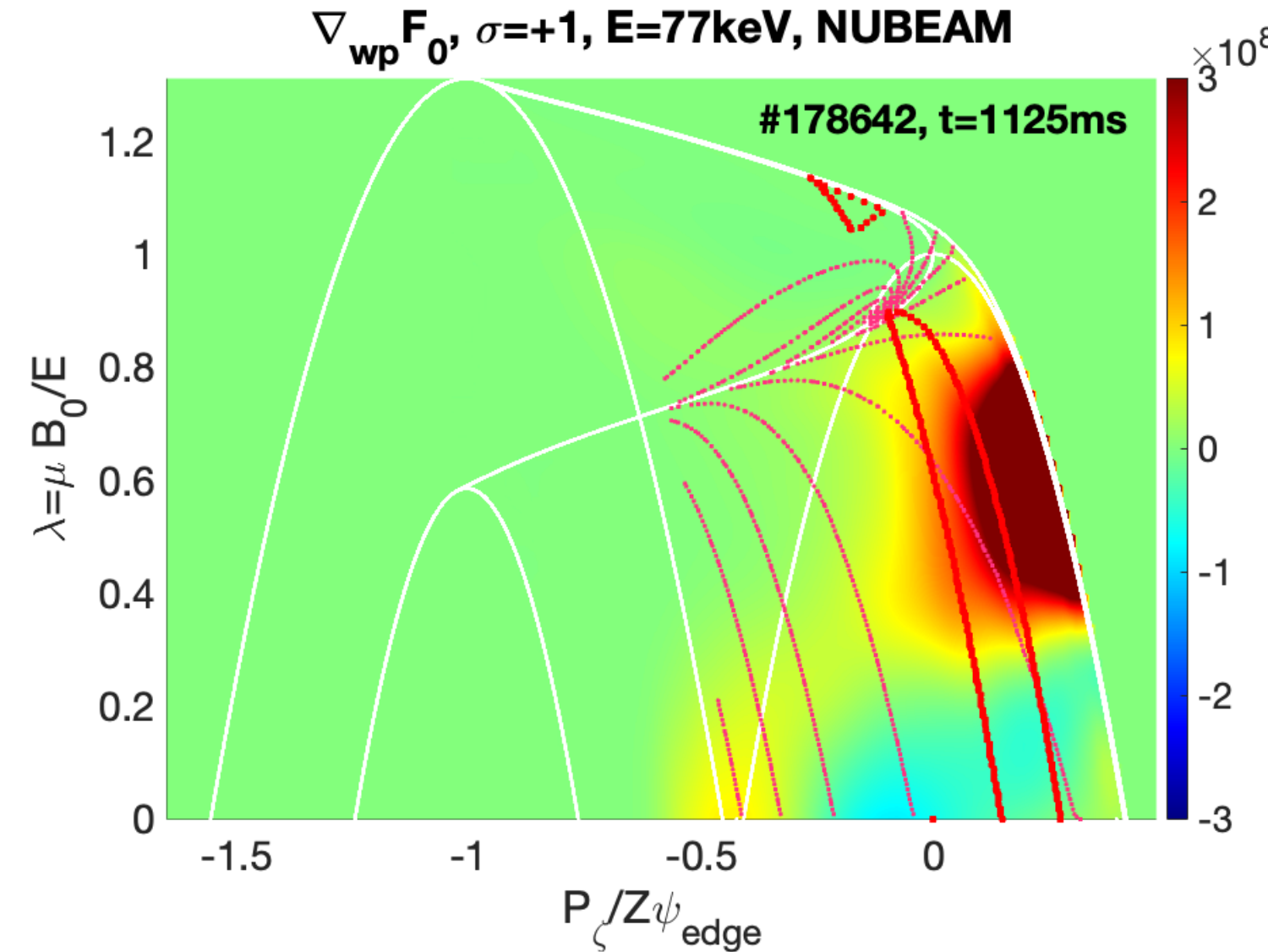
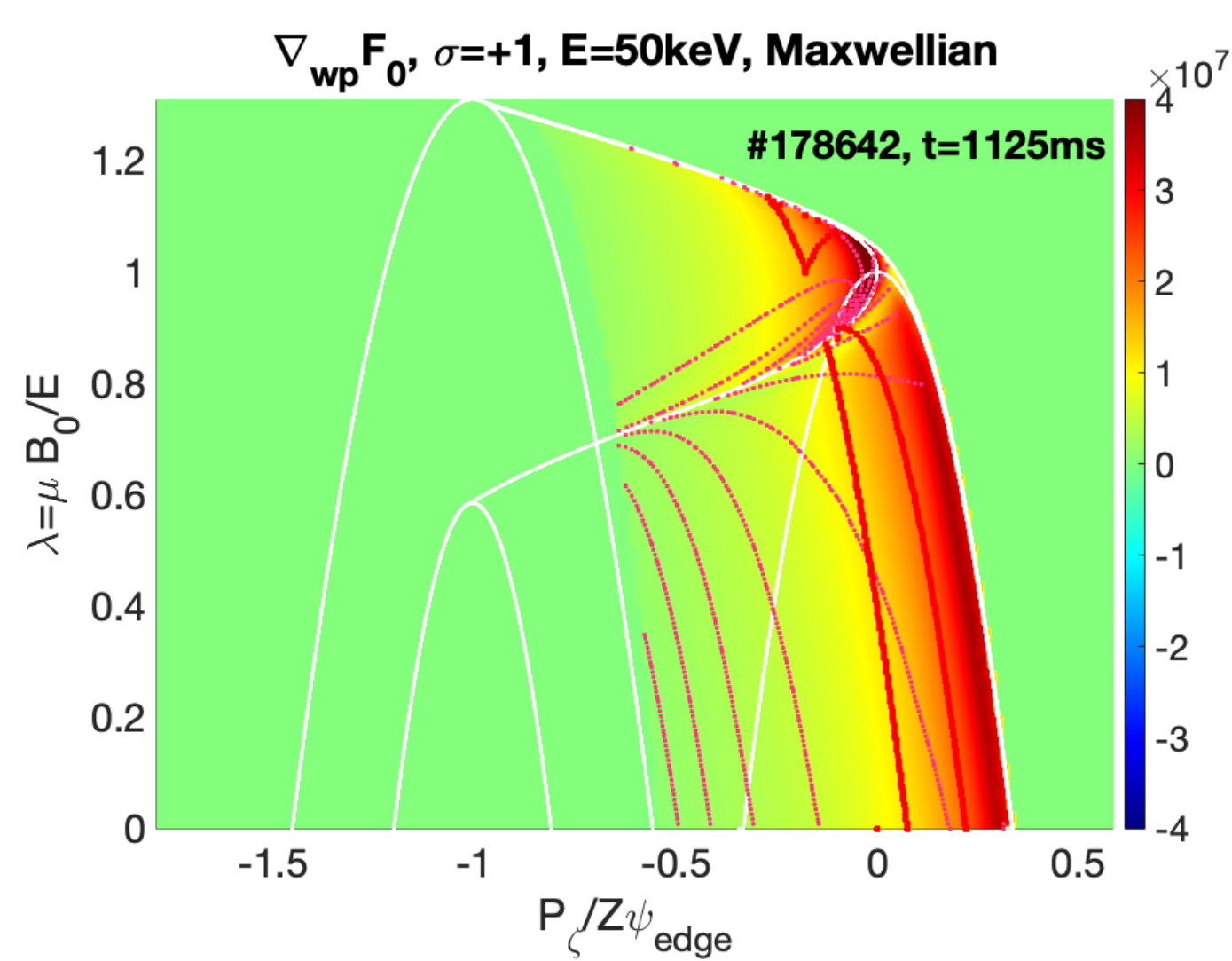
$$\nabla F|_{\mu, v_{||}} = \nabla P_\phi|_{\mu, v_{||}} \frac{\partial F}{\partial P_\phi} + \nabla \lambda|_{\mu, v_{||}} \frac{\partial F}{\partial \lambda} + \nabla E|_{\mu, v_{||}} \frac{\partial F}{\partial E}$$

Maxwellian approximation strongly impacts BAE stability



- Linear **GTC** and **M3D-C1** simulations performed for **t=1125ms**, with the **original EFIT reconstruction** featuring reverse q profile with $q_{min} = 1.45$
- A dominant **n=4,m=6** is **obtained**, while in the **experiment** a **n=5, m=7** is **observed**, due to ± 0.05 **uncertainty on q_{min}**
- Over this **numerical test**, **GTC** and **M3D-C1** **linear results** are **very similar**
- **Both codes** shows that the **Maxwellian approximation lowers by a factor of 2** the BAE growth rate
- The mode frequency is **weakly affected**, as expected from a **gap mode**

Maxwellian drive significantly lower at high energy



➤ The beam drive is much **stronger** than its Maxwellian counterpart

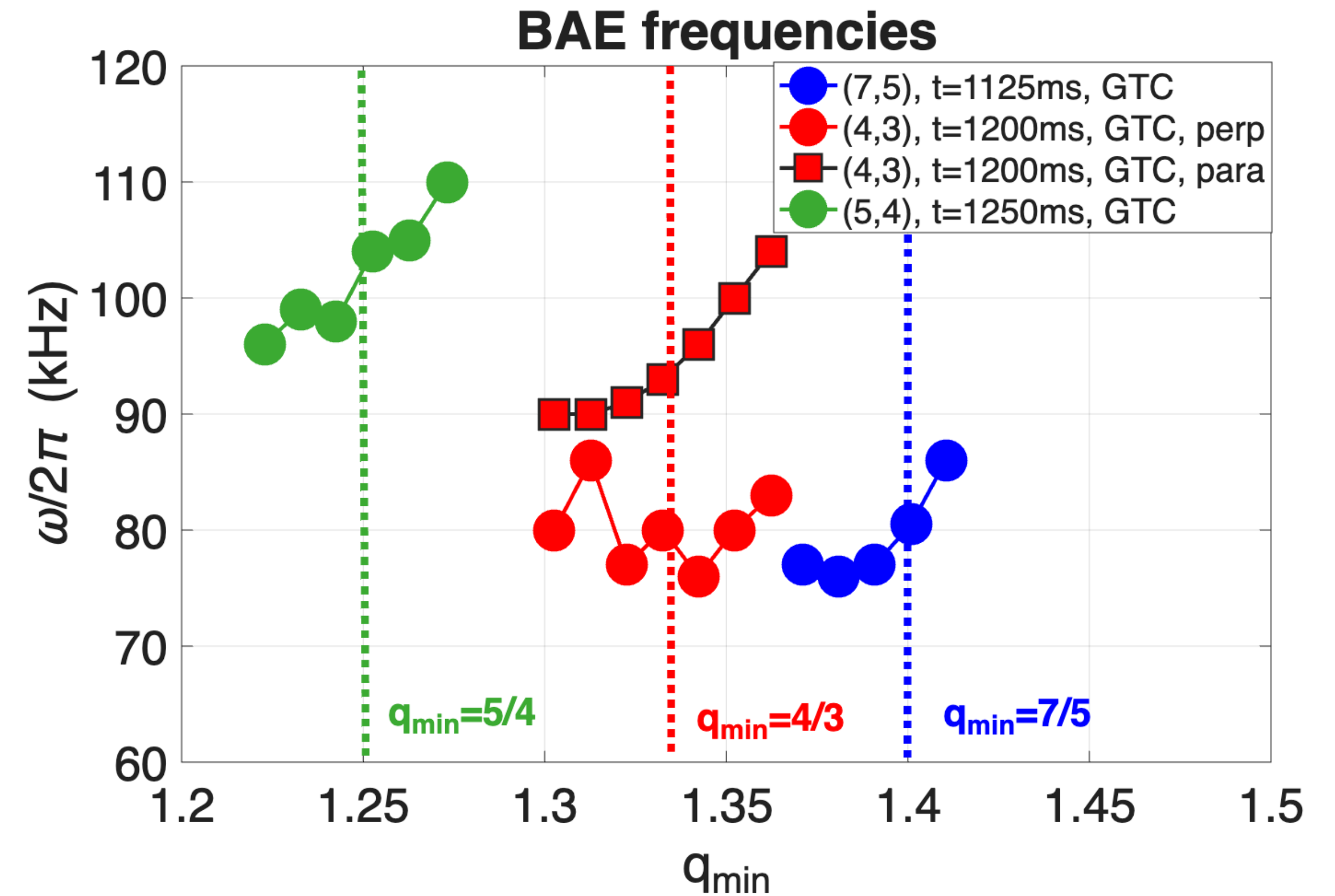
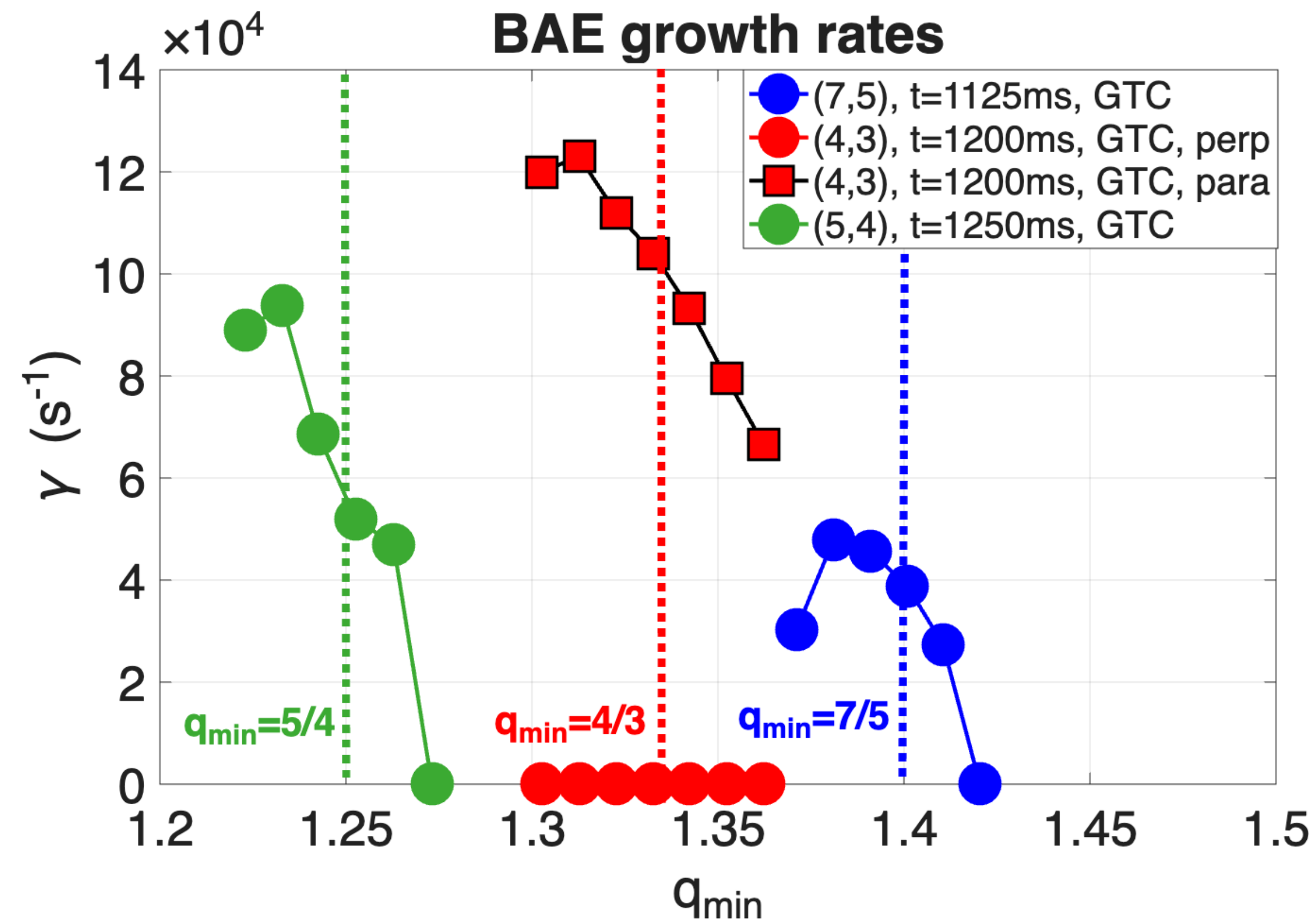
➤ **Less resonances** are available for the beam case, due to its **anisotropy**

➤ **Resonant structures** obtained with **GTC** align **exactly** with expected resonances for $n=4$ and $f=75\text{kHz}$

➤ The **strength** of the beam $\nabla_{wp} F_0$ explains the **stronger BAE drive**, despite less resonances available

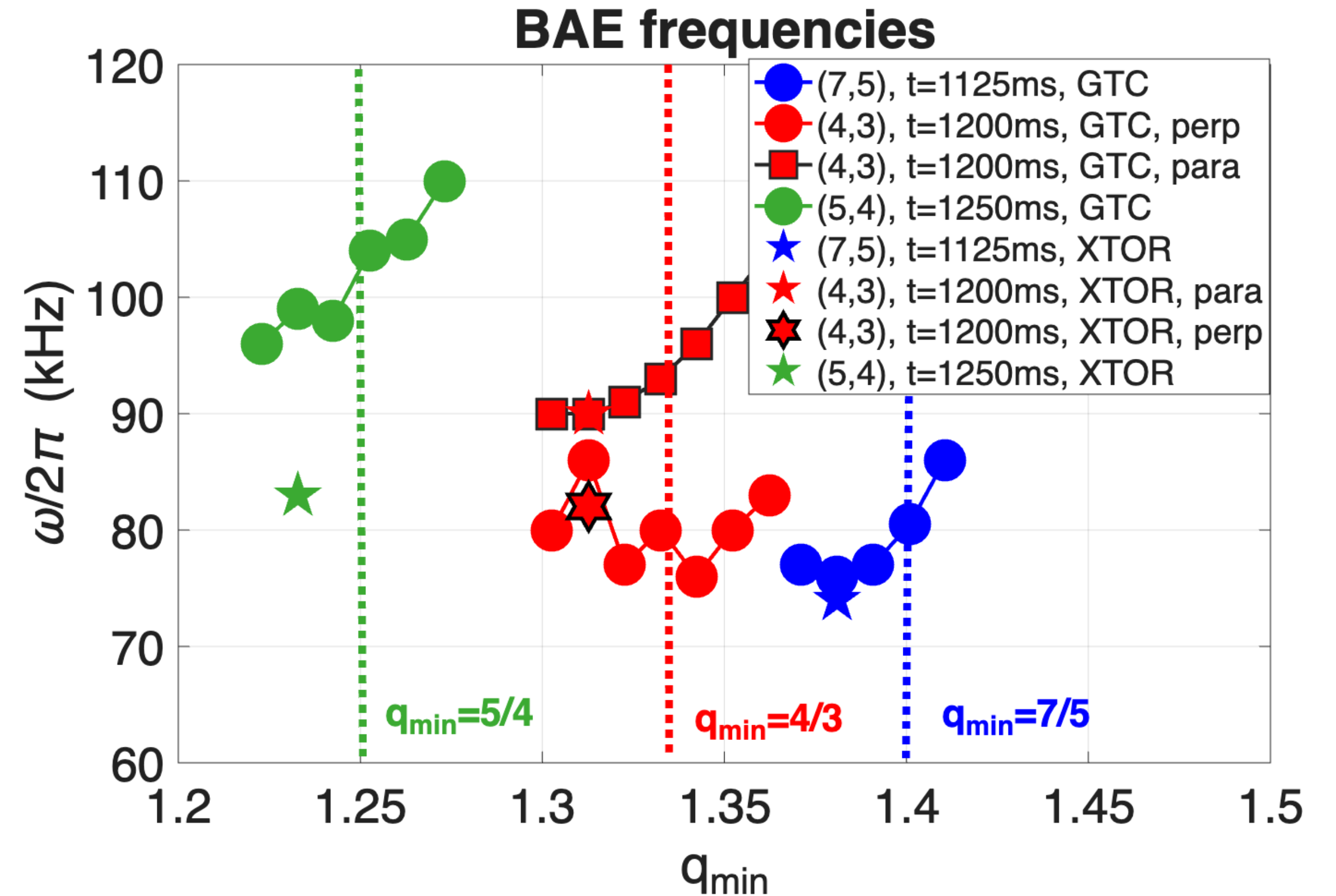
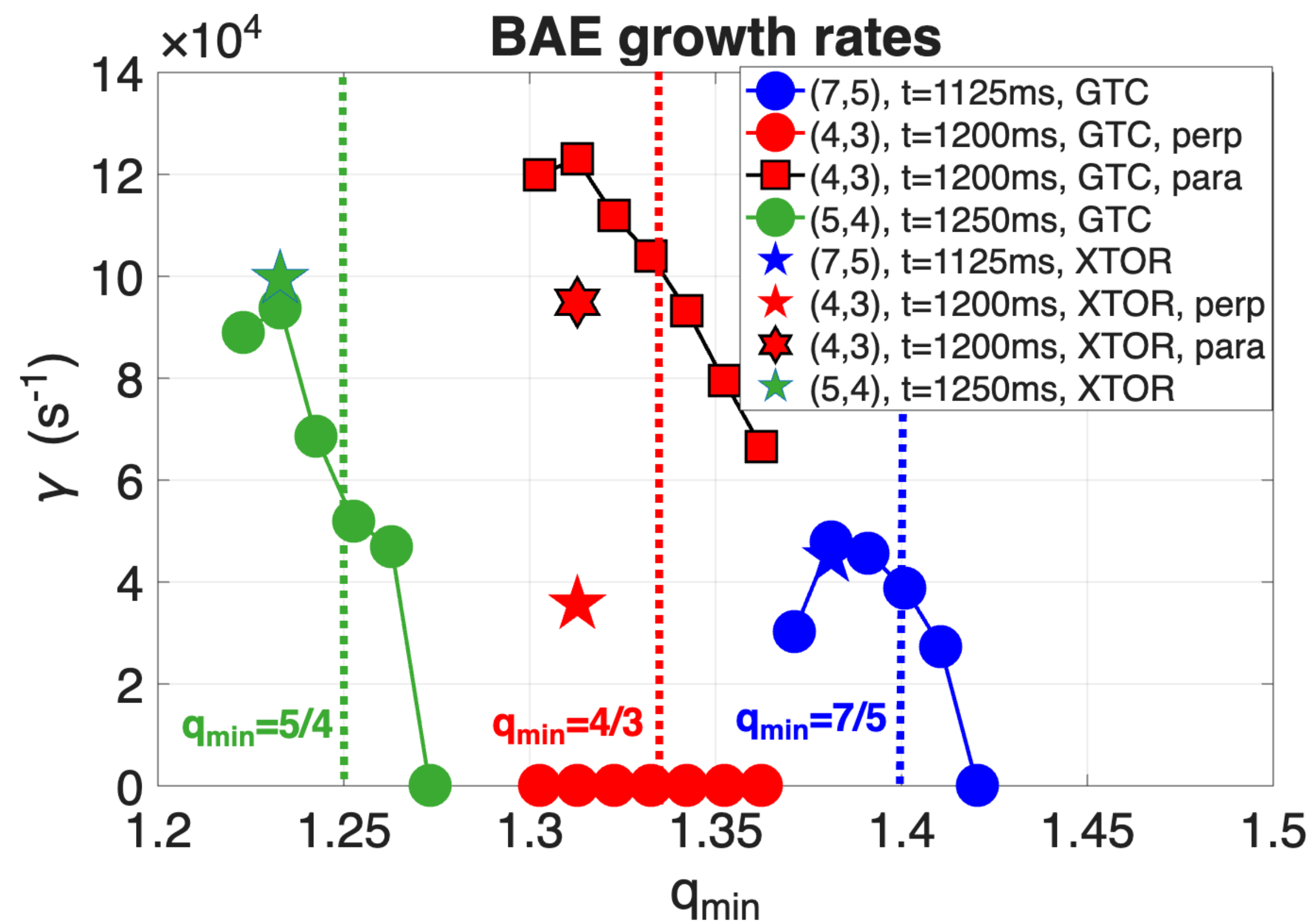
➤ With **original EFIT** and **neoclassical NUBEAM** inputs, the **BAE stability** is **barely changed** on the **considered time windows**

Validation obtained on BAE stabilisation



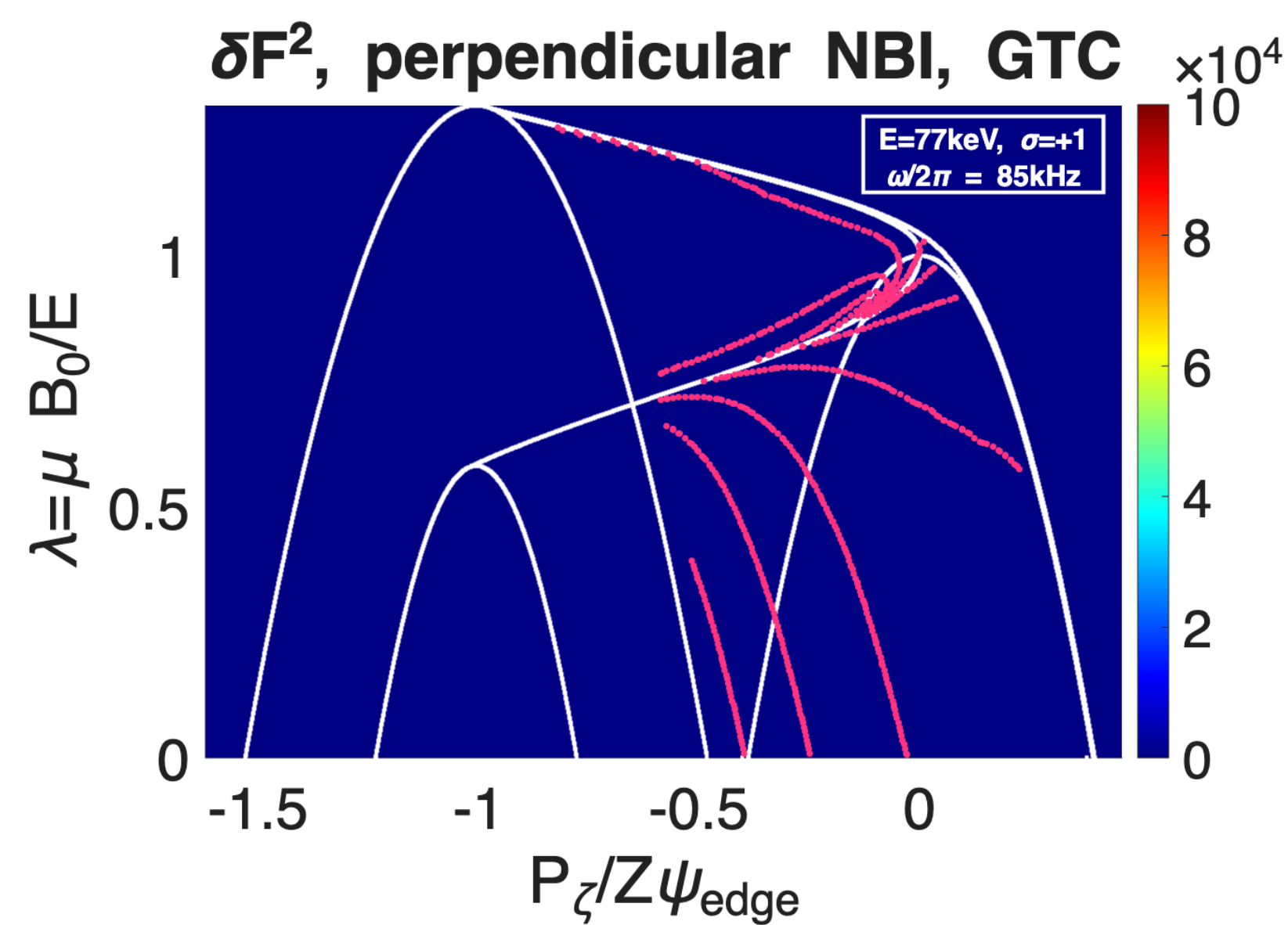
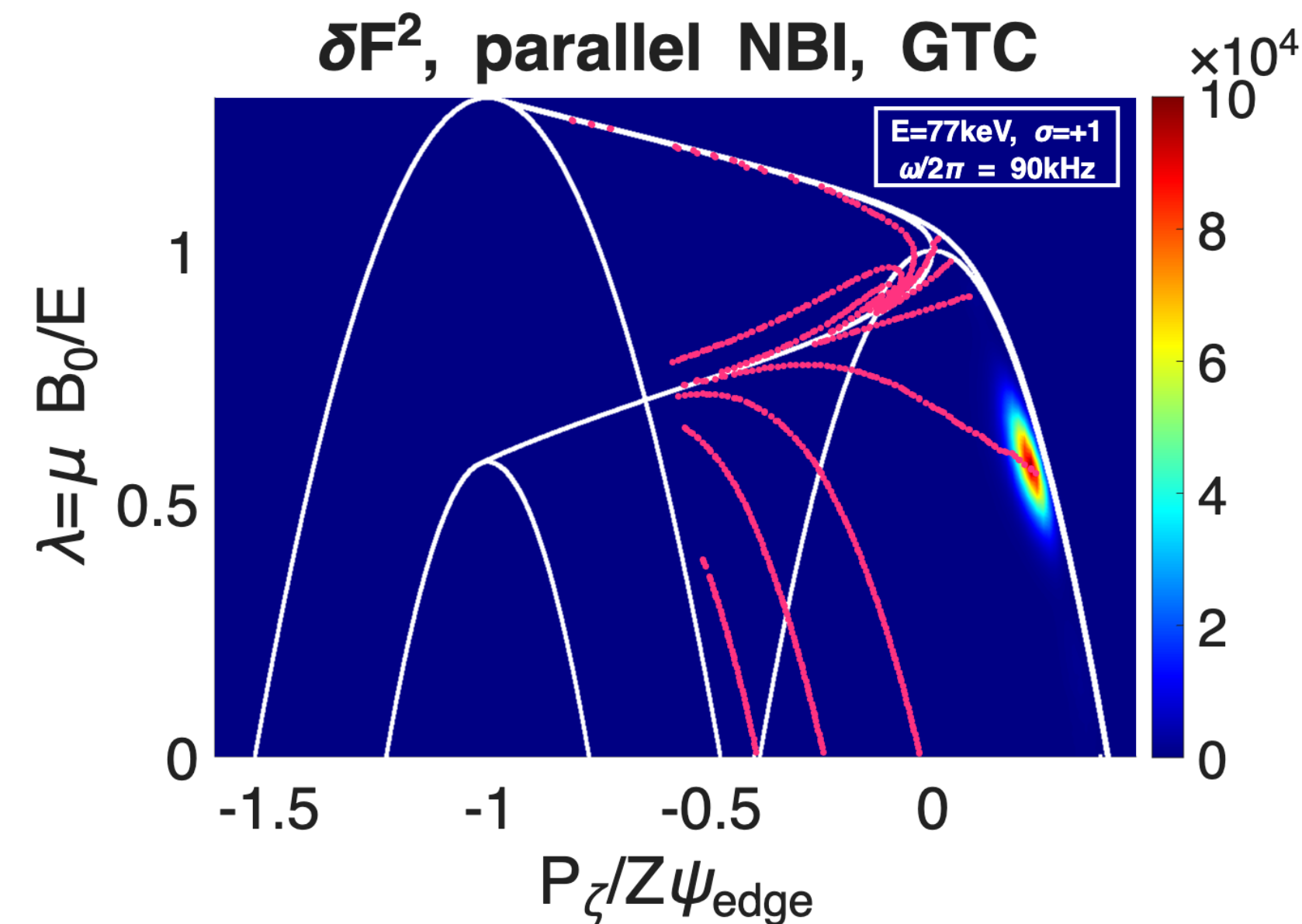
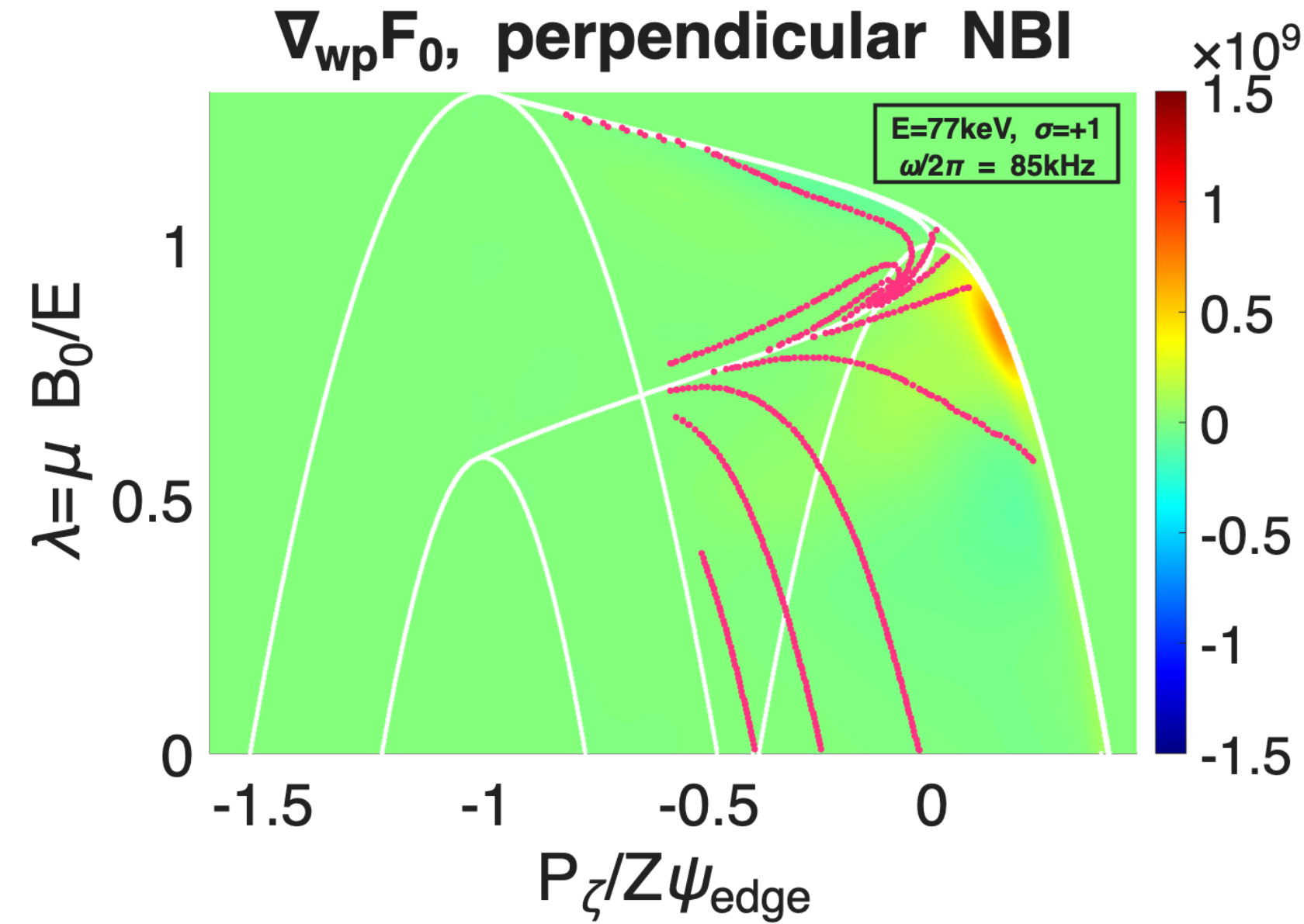
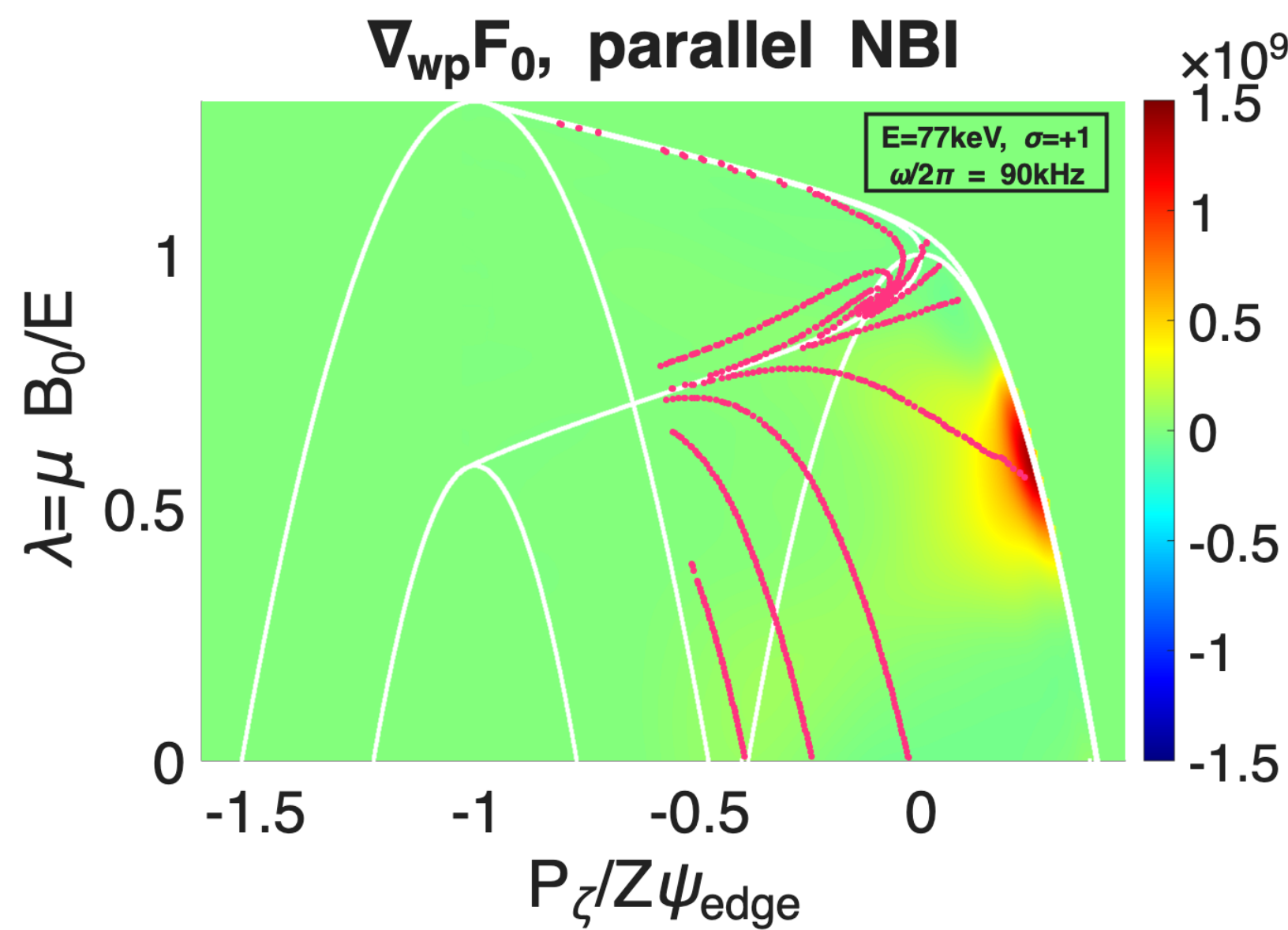
- **Relaxed NUBEAM** distributions including **ECE-based diffusivity now used**, over a $q_{\min}$ scan enabled by the CHEASE equilibrium code
- The same **BAE** (m, n) **modes**, and the **BAE stabilisation** under **perpendicular beam** injection are **recovered by GTC**

Validation obtained on BAE stabilisation



- **Relaxed NUBEAM** distributions including **ECE-based diffusivity now used**, over a q_{min} scan enabled by the CHEASE equilibrium code
- The same **BAE** (m, n) **modes**, and the **BAE stabilisation** under **perpendicular beam** injection are **recovered by GTC**
- **XTOR** recovers **very similar stability results**, but with **marginally unstable BAE** at t=1200 under the **perpendicular NBI**, potentially due to the code **full-f** nature

BAE stabilisation due to absent drive at resonances



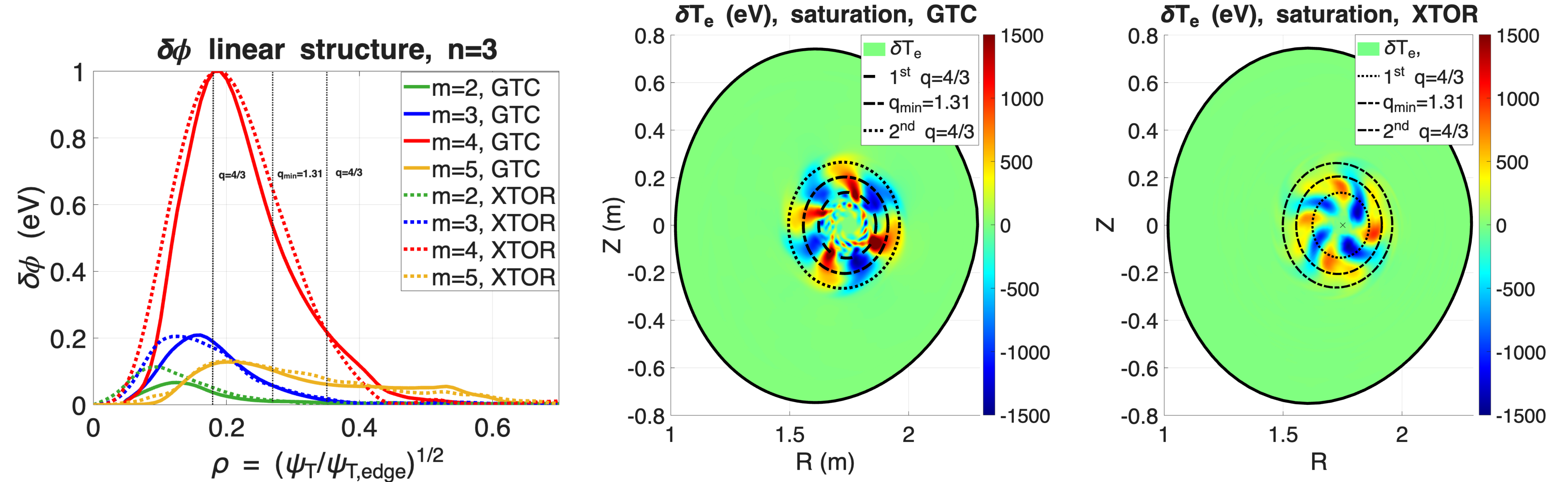
➤ Under **perpendicular** beam injection, the **EP drive** move towards **larger $\lambda = \mu B_0 / E$** values

➤ **The perpendicular EP drive sits right in-between** wave-particle resonances

➤ It **kills the BAE drive** compared to the parallel injection case, since **no resonances are excited**

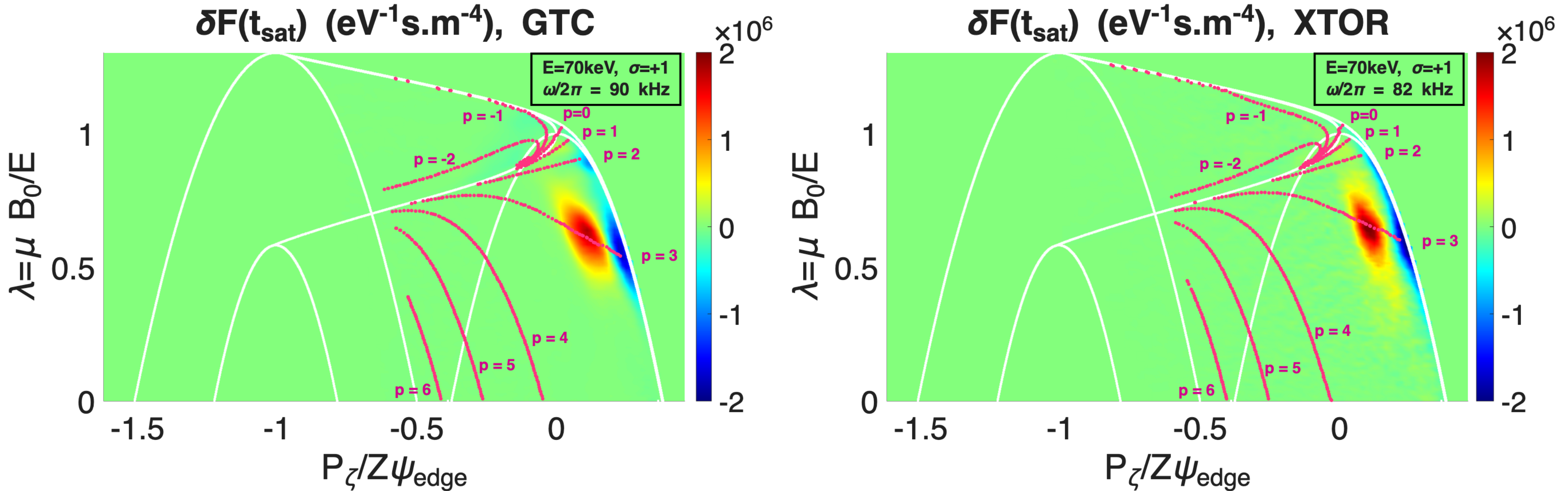
➤ The **BAE stabilisation in DIII-D** is indeed due to **modifications of the EP phase space distribution**

Linear and nonlinear XTOR-GTC verification



- **XTOR and GTC linear/nonlinear results** are compared for **t=1200ms with parallel NBI**
- The **linear BAE mode structures** are in **quantitative agreement** between the codes
- In both codes, the **BAE saturates (overshoot)** at similar amplitudes $\delta T_E \sim 1.5$ keV

Phase space transport GTC-XTOR verification



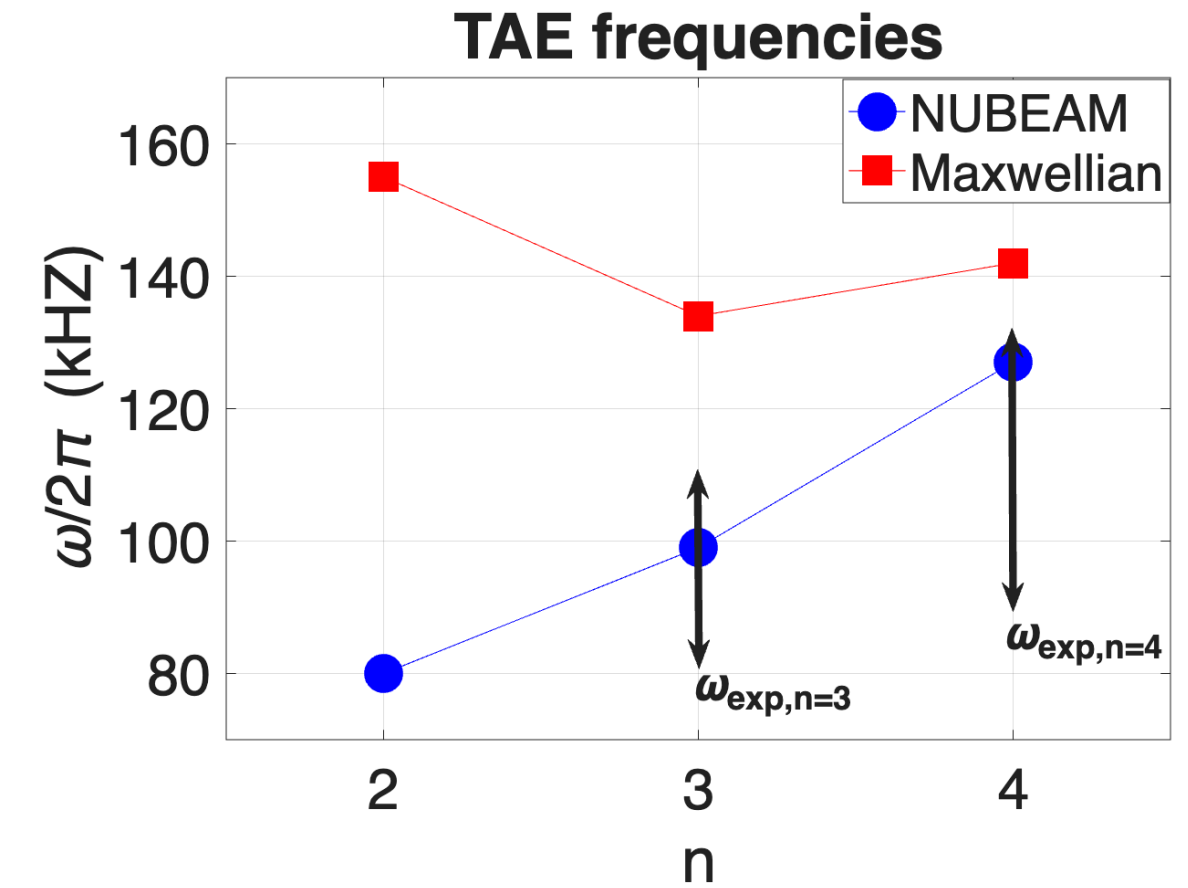
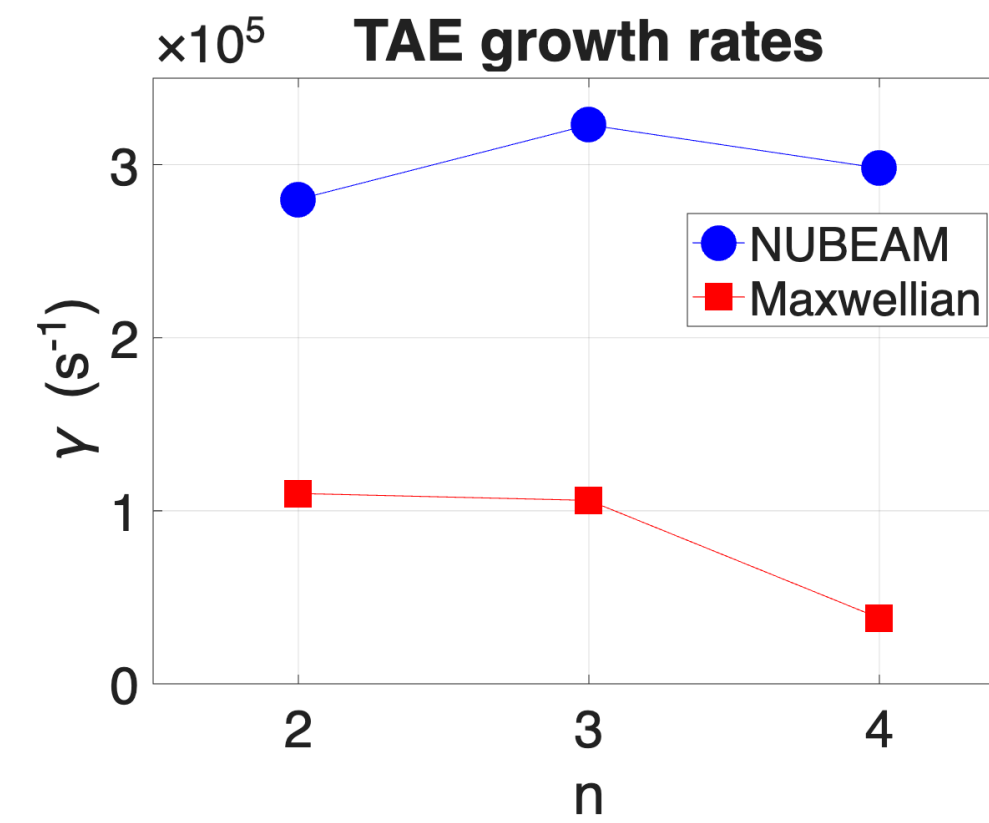
- The **perturbed distributions** in **CoM** space, or **phase space zonal structures** [1], are in **quantitative agreement** in both **shape** and **amplitude** at **BAE saturation**
- These results provide a **detailed V&V** of **BAE simulations** for these two codes **against DIII-D experiments**

Conclusions

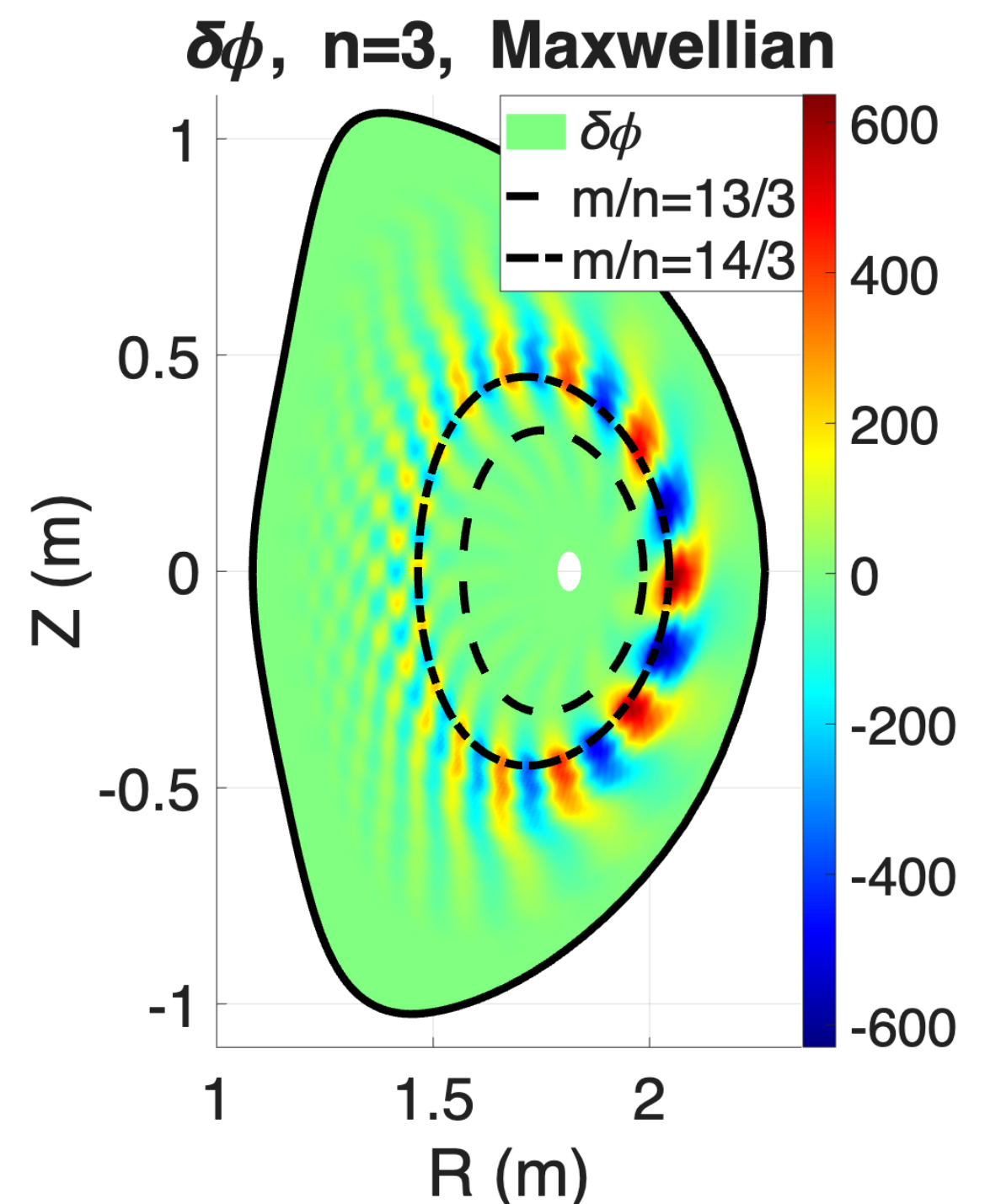
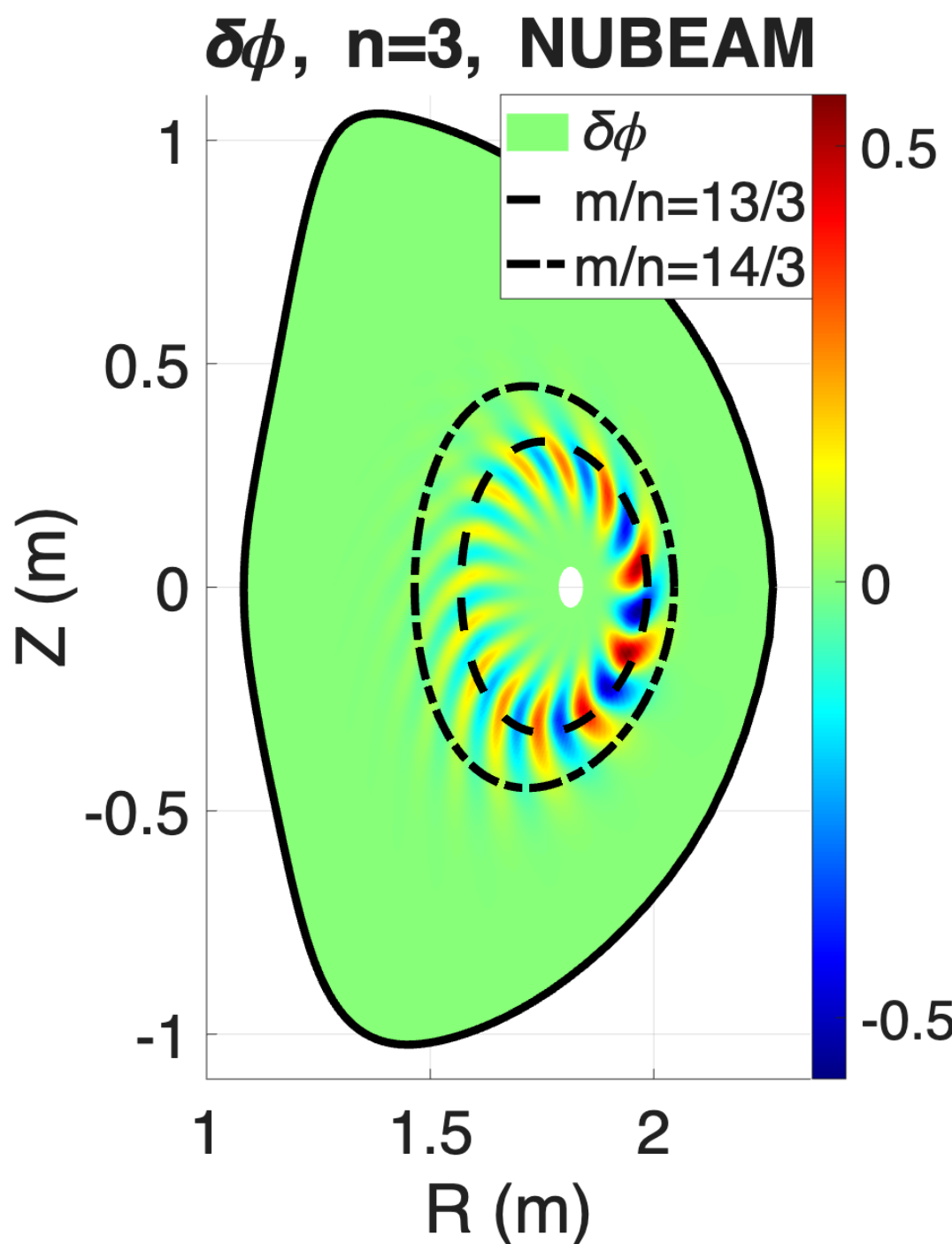
- A **DIII-D discharge** with **BAEs** sensitive to **beam injection angle** have been chosen as a **V&V case to verify the use of realistic EP distributions** within the ITPA-EP community
- The **NUBEAM** and **EPCoM codes** are used to **model realistically** EP distributions in **CoM space**, where the **EP drive and resonances** can be explicitly shown
- **Realistic** EP distributions have a **strong impact on BAE stability** compared to equivalent **Maxwellians**, due to **stronger drive at injection energy**
- The **BAE stabilization** under perpendicular NBI is **reproduced** in **GTC** and **XTOR simulations**, and due to **misalignment** between **EP drive** and **wave-particles resonances**
- **Quantitative** linear and nonlinear **agreements obtained** for **GTC** and **XTOR** BAE simulations

Perspectives

➤ **Cross-scale** gyrokinetic simulations will be performed with **realistic EP distributions** to understand **confinement improvement** in **DIII-D [1]** and **JET-DT [2]** plasmas



➤ Initial results for the **DIII-D** case shows the **importance** of **realistic EP input** for modelling the **TAEs**



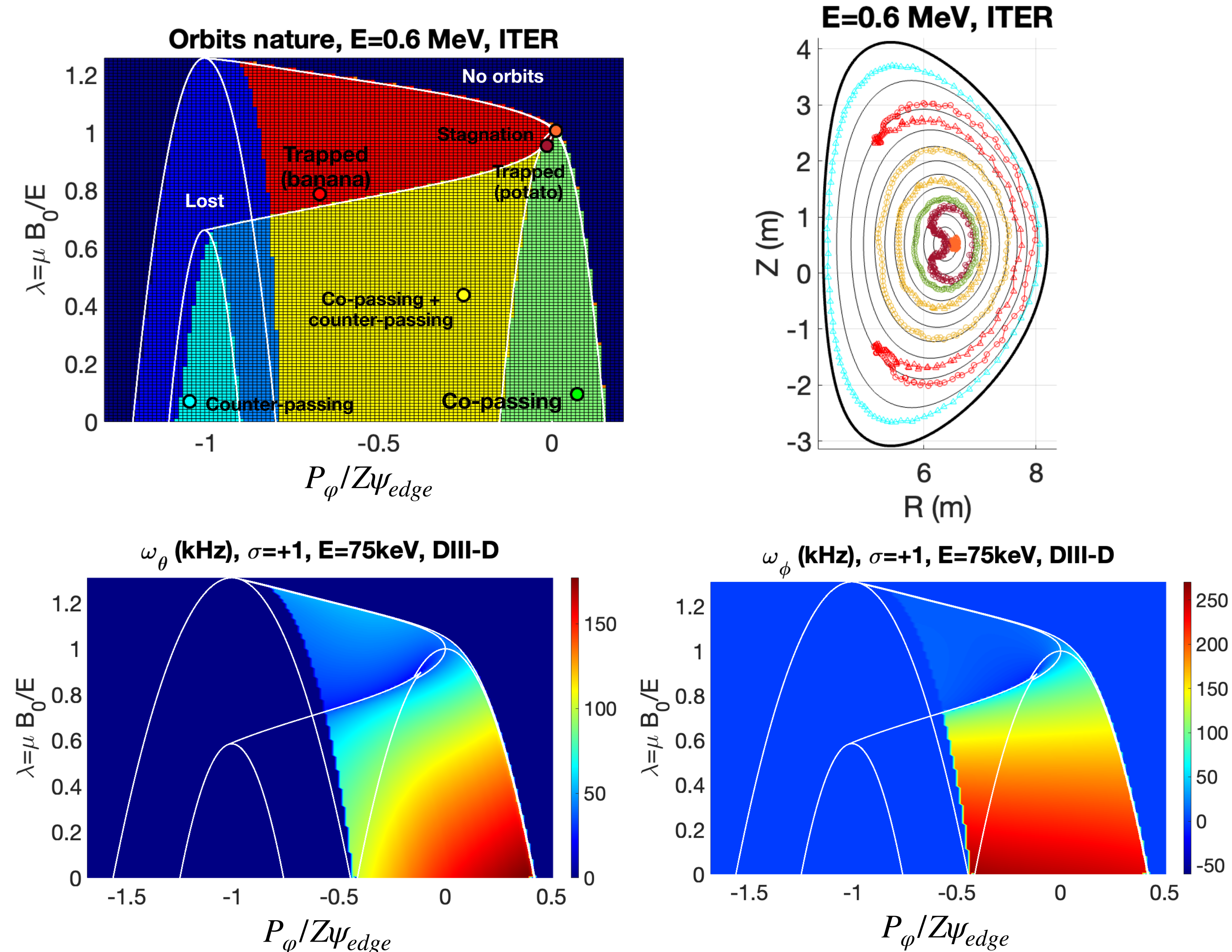
➤ **Considering realistic EP input** is therefore **essential** to analyse even **qualitatively confinement improvement** with cross-scale simulations

[1] X. Du et al. 2025, *Phys. Rev. Lett.*

[2] J. Garcia et al. 2024, *Nat. Comm.*

Back-up slides

3D CoM grid and orbits database



➤ A 3D ($+\sigma = \pm 1$) cartesian grid in CoM space is **chosen**, preventing **singularities** [1]

➤ For each CoM grid point, the (p, R, Z) **orbits** are stored over 1 poloidal orbit time

➤ Allows transformation from **CoM space** to **any coordinate systems**

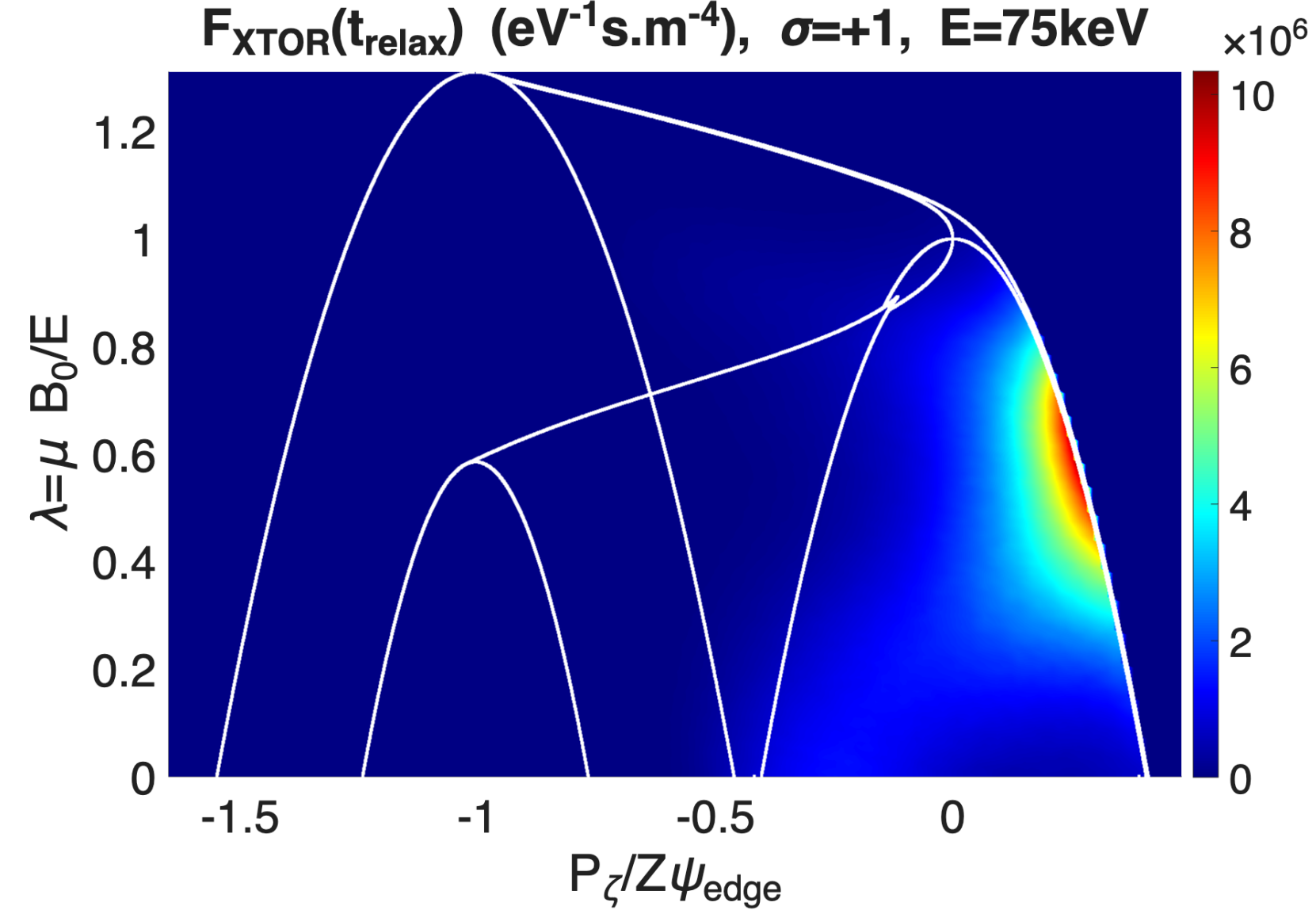
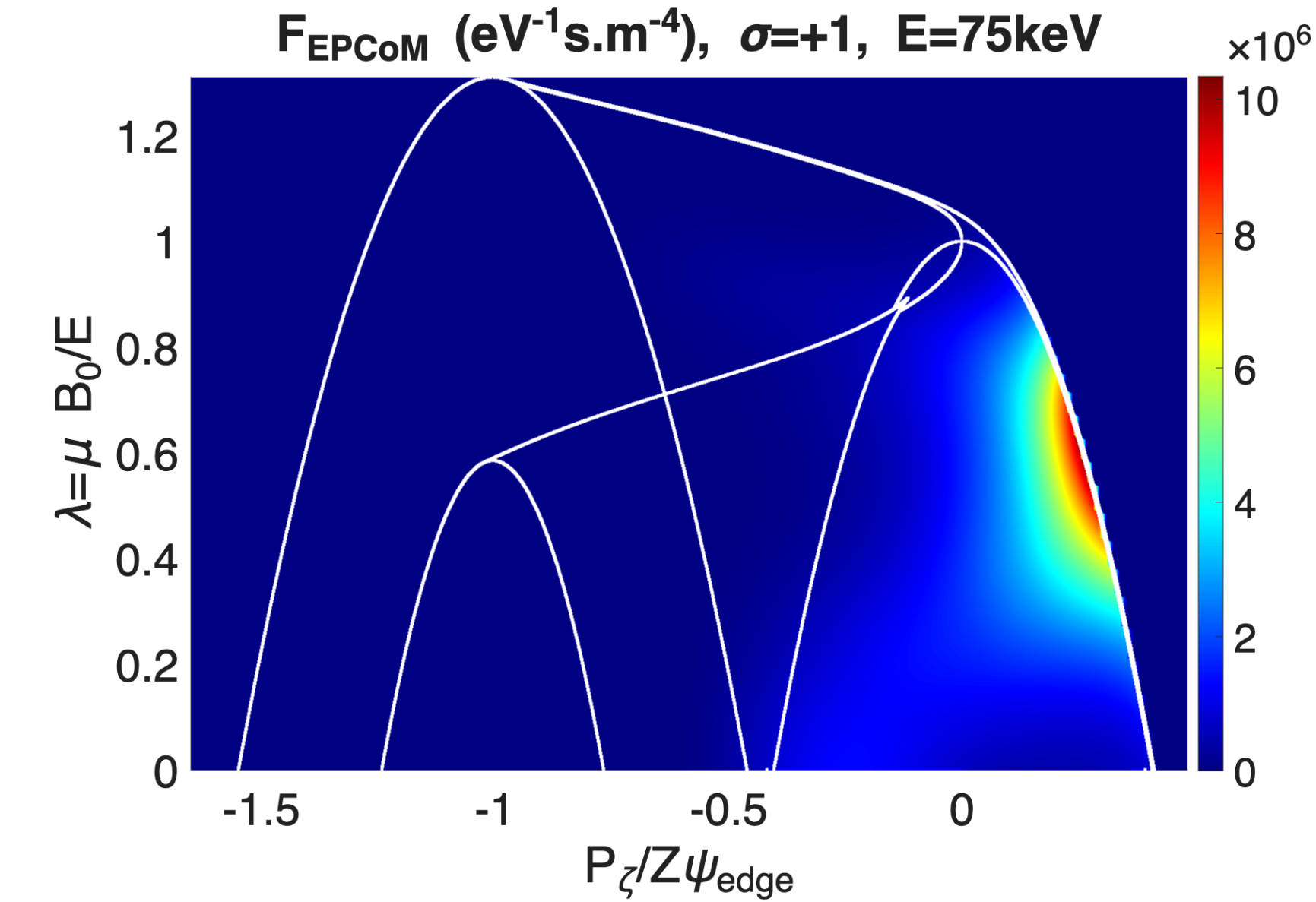
➤ EP frequencies $(\omega_\theta, \omega_\phi)$ can be obtained through **orbit analysis** $(\theta(t), \varphi(t))$ traces)

➤ These mappings enable to **draw 2D resonant plans** for a given (ω, n)

$$\omega = n\omega_\phi(P_\phi, \lambda, E) - p\omega_\theta(P_\phi, \lambda, E) \quad p \in \mathbb{Z}$$

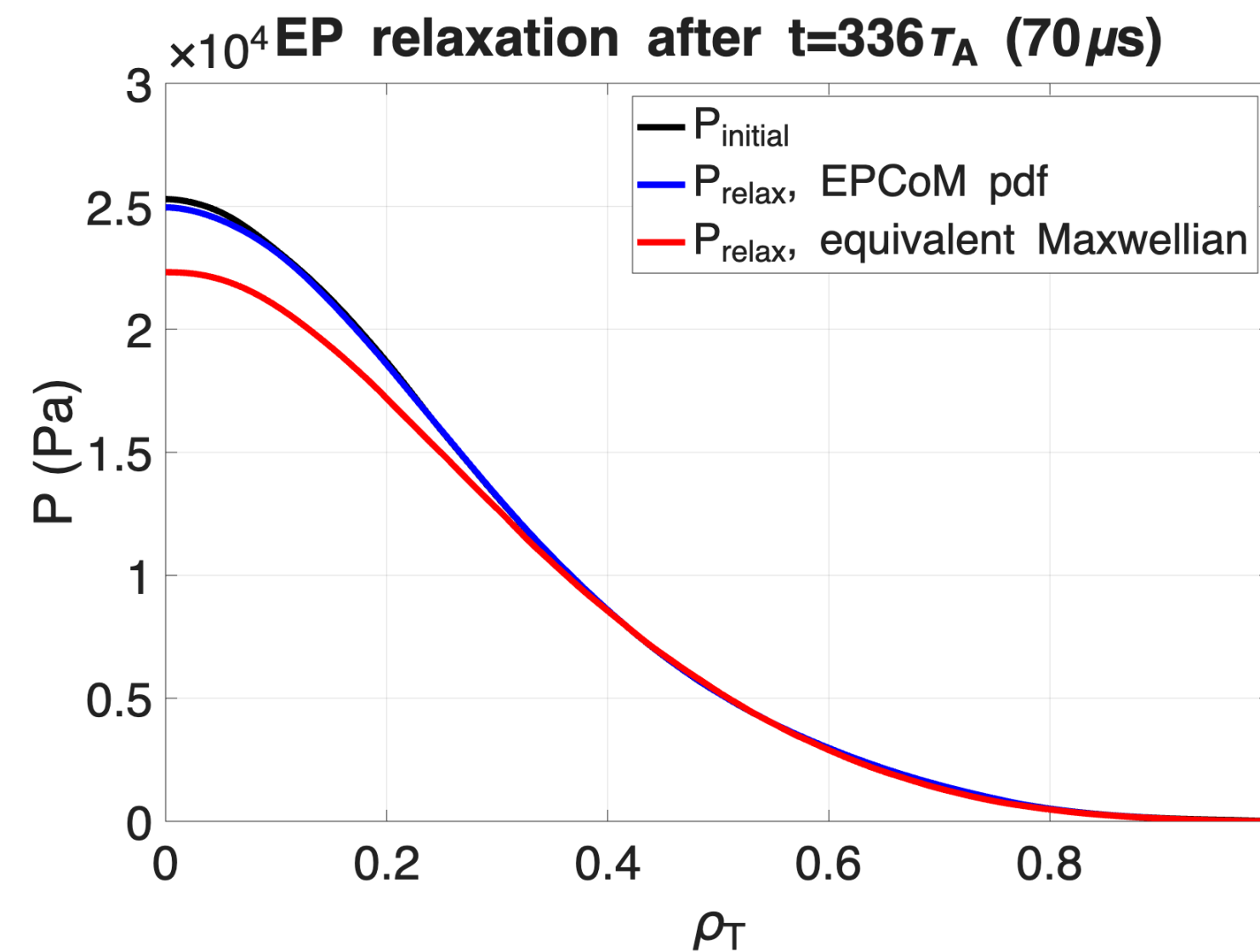
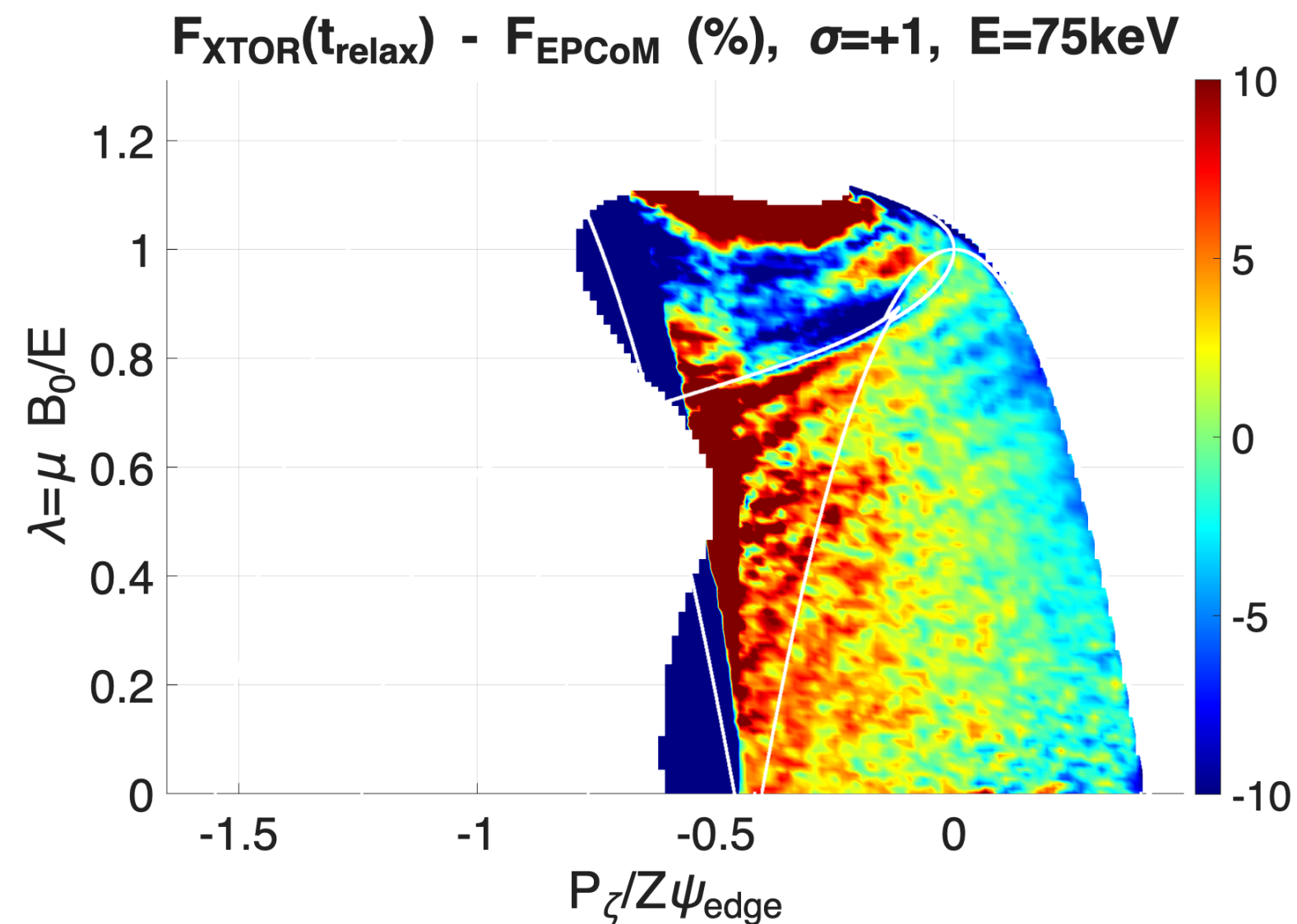
[1] A. Bierwage et al. 2022, *Comp. Phys. Comm.*

Initialization of EPCoM pdf in XTOR-K



➤ EPs can be loaded in XTOR-K using a **6D Monte-Carlo method**, pulling randomly **($\mathbf{X}$, $\mathbf{V}$)**, computing **CoM coordinates** and using F_{EPCoM} as **control function**

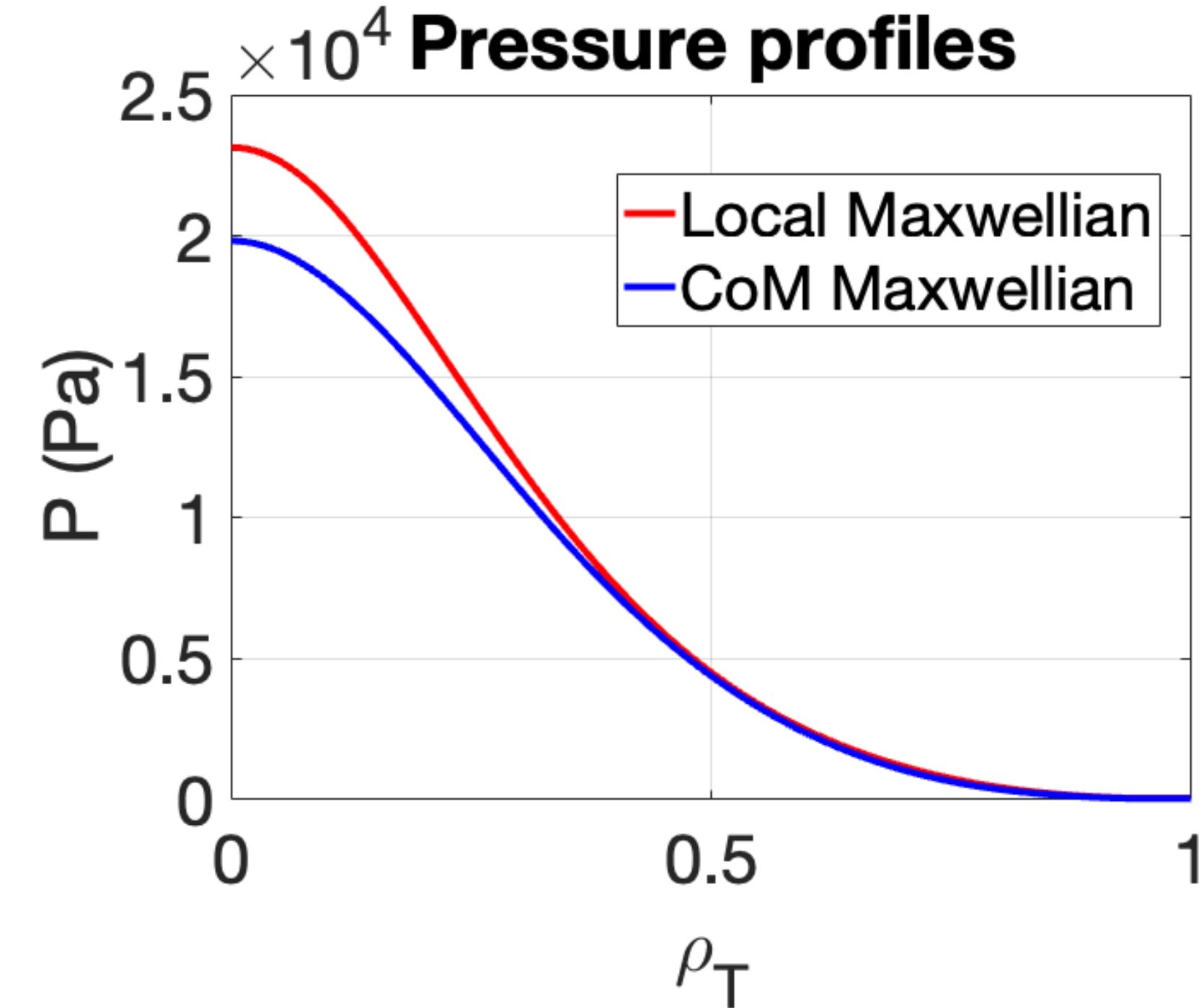
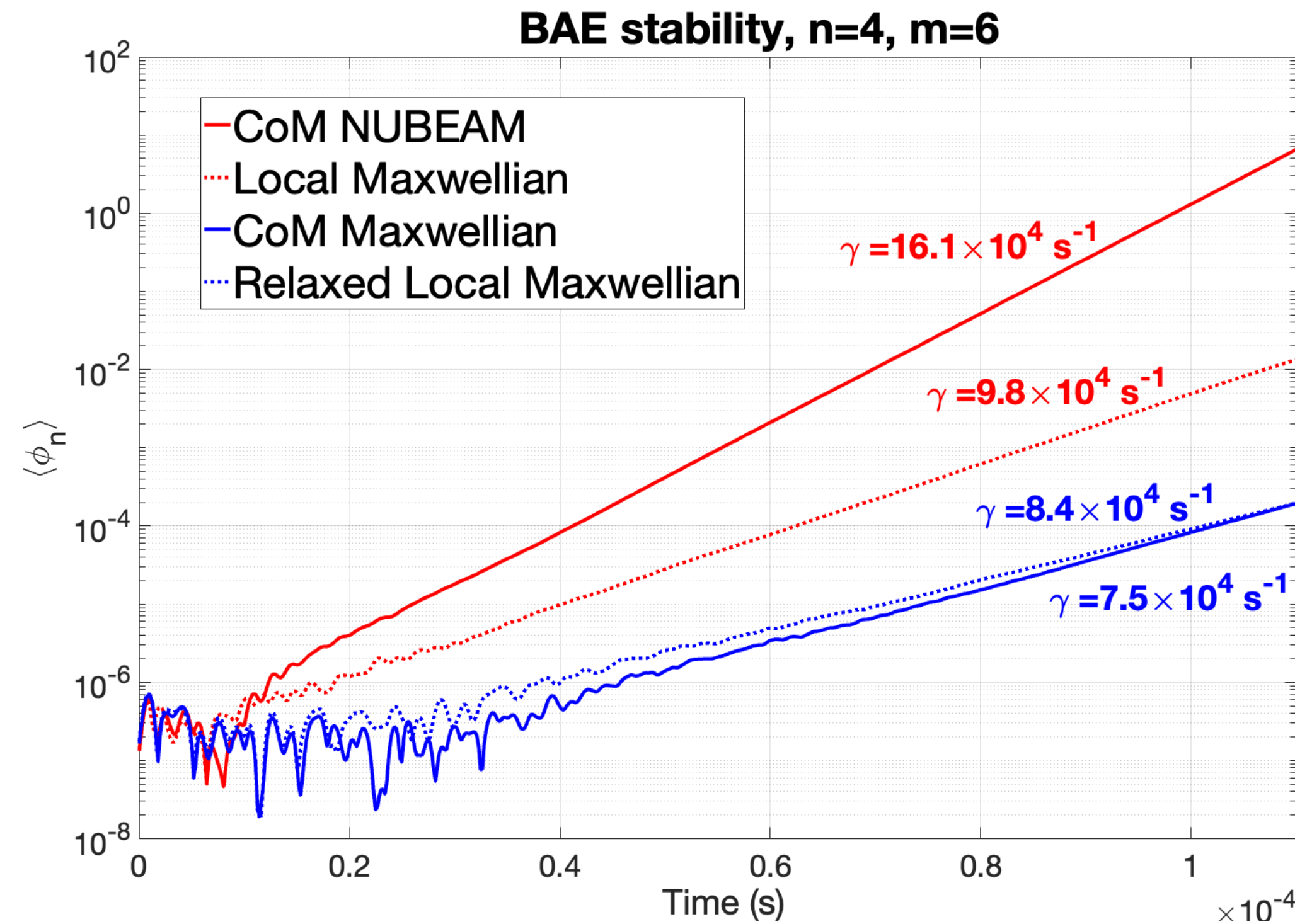
➤ Using 256M markers, **EP loading is successful**



➤ After $t_{\text{relax}} = 334\tau_A = 70\mu\text{s}$, the **EP pdf remains stationery**, as expected

➤ **Comparatively**, the **equivalent Maxwellian** undergoes **significant relaxation**

CoM capability successfully tested in GTC



- **GTC** BAE linear simulations conducted with **CoM NUBEAM**, **local Maxwellians** and **CoM maxwellian** distributions
- **NUBEAM distribution** and its equivalent **local Maxwellian** yield quite different **BAE stability**, as expected
- **Stability results** are however **very similar** between the **CoM** and **relaxed local Maxwellians** → **CoM chain rule successfully tested in GTC**
- Even in this limit, results are **not identical** due to the **inclusion of EP drifts** (neoclassical effects)

True kinetic equilibrium requirements

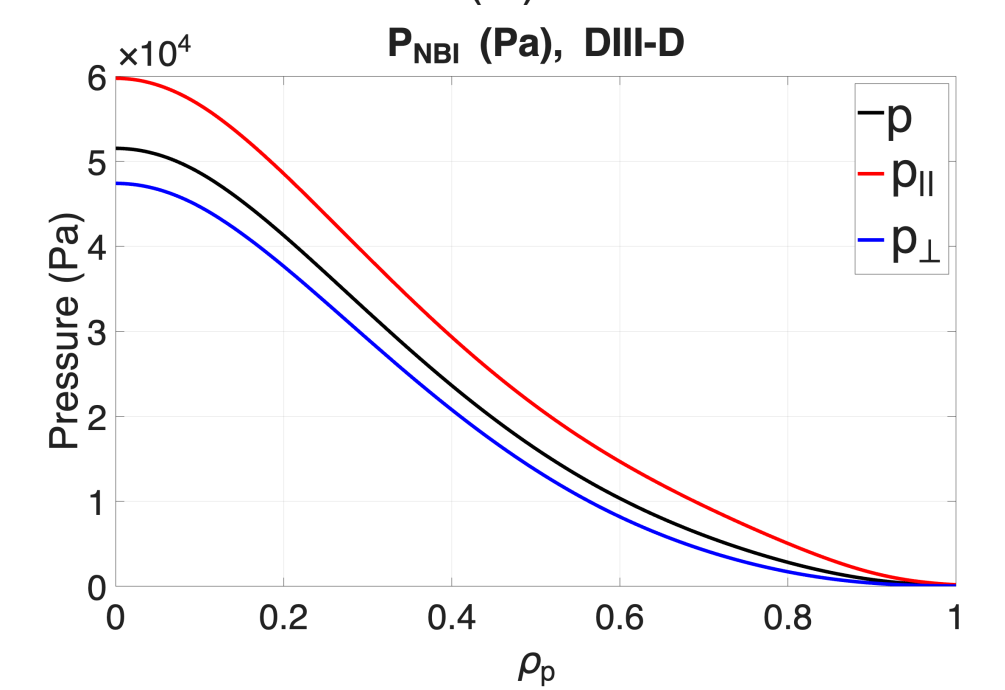
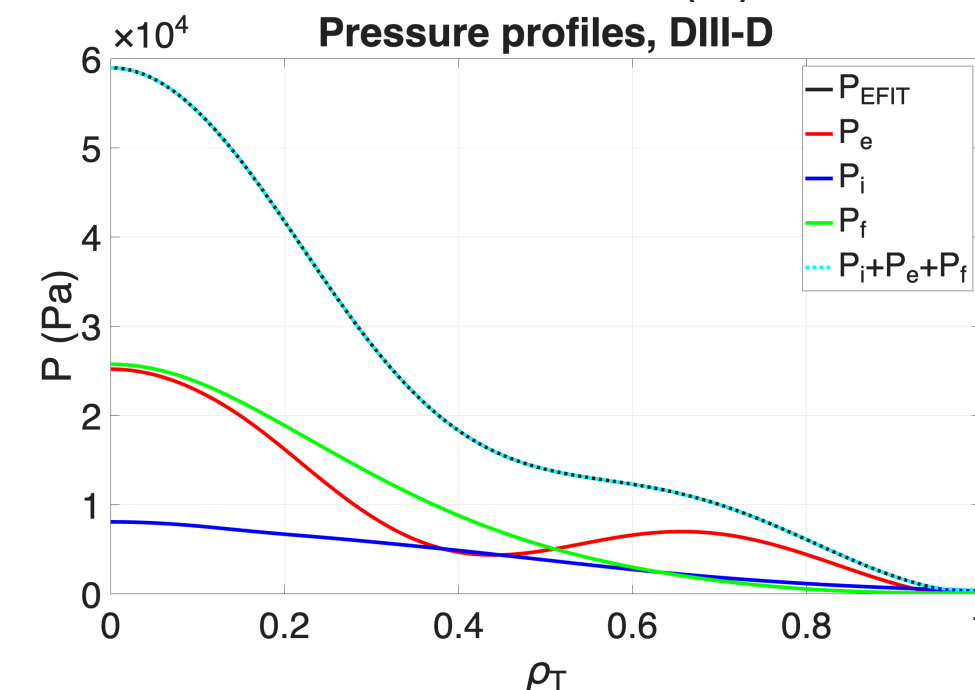
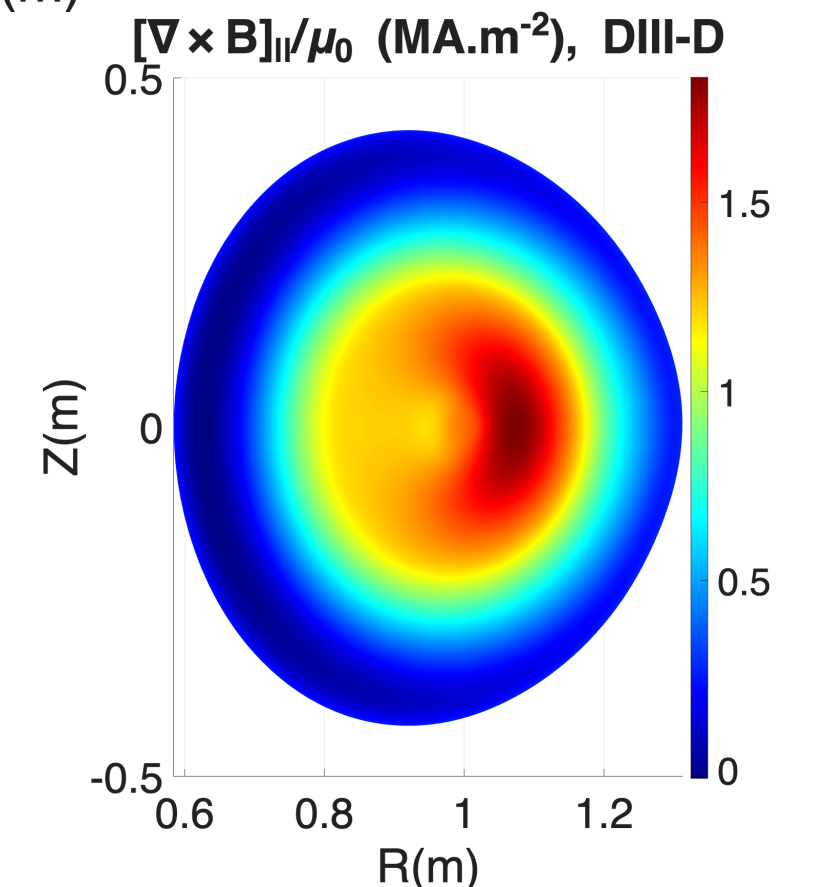
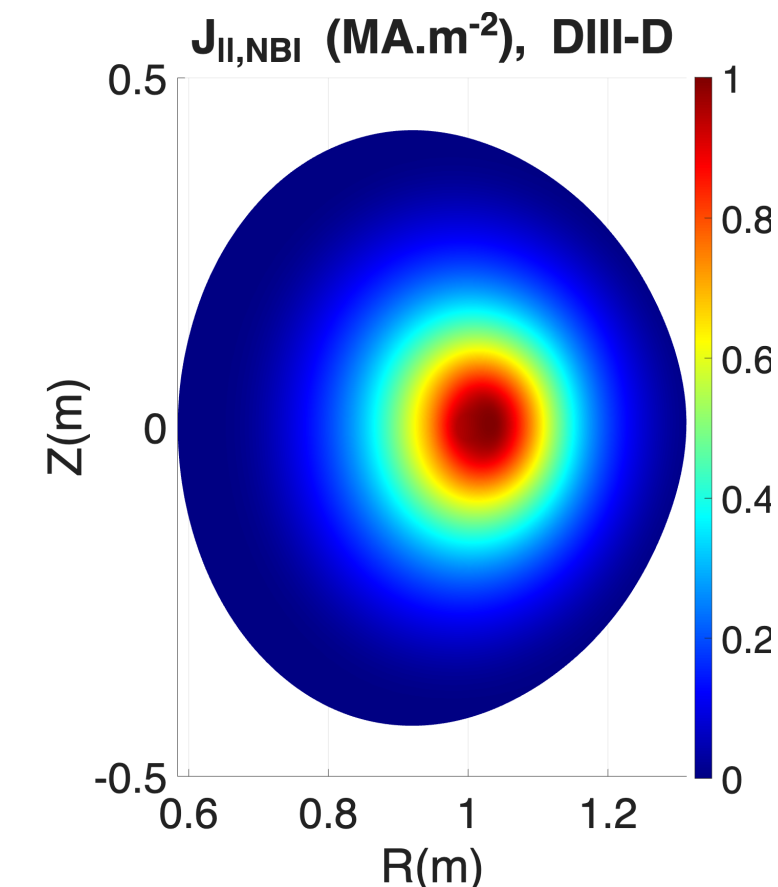
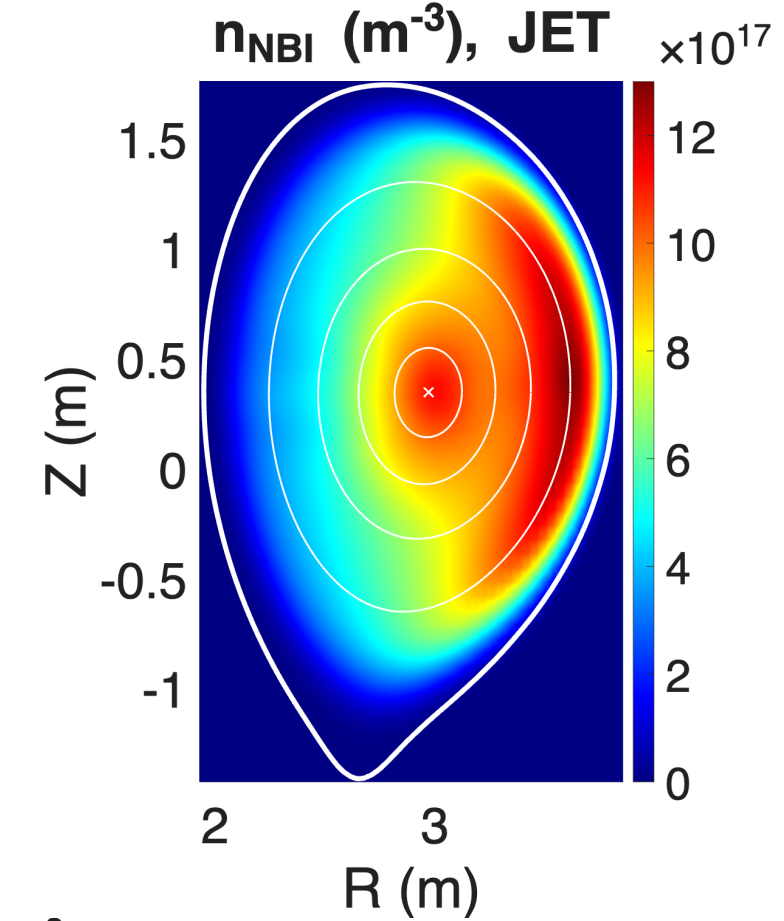
➤ Since XTOR's kinetic module is **full-F**, a true **kinetic-MHD equilibrium** needs to be **initialised** at the **start of the simulation**, otherwise **blow-outs** may occur

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

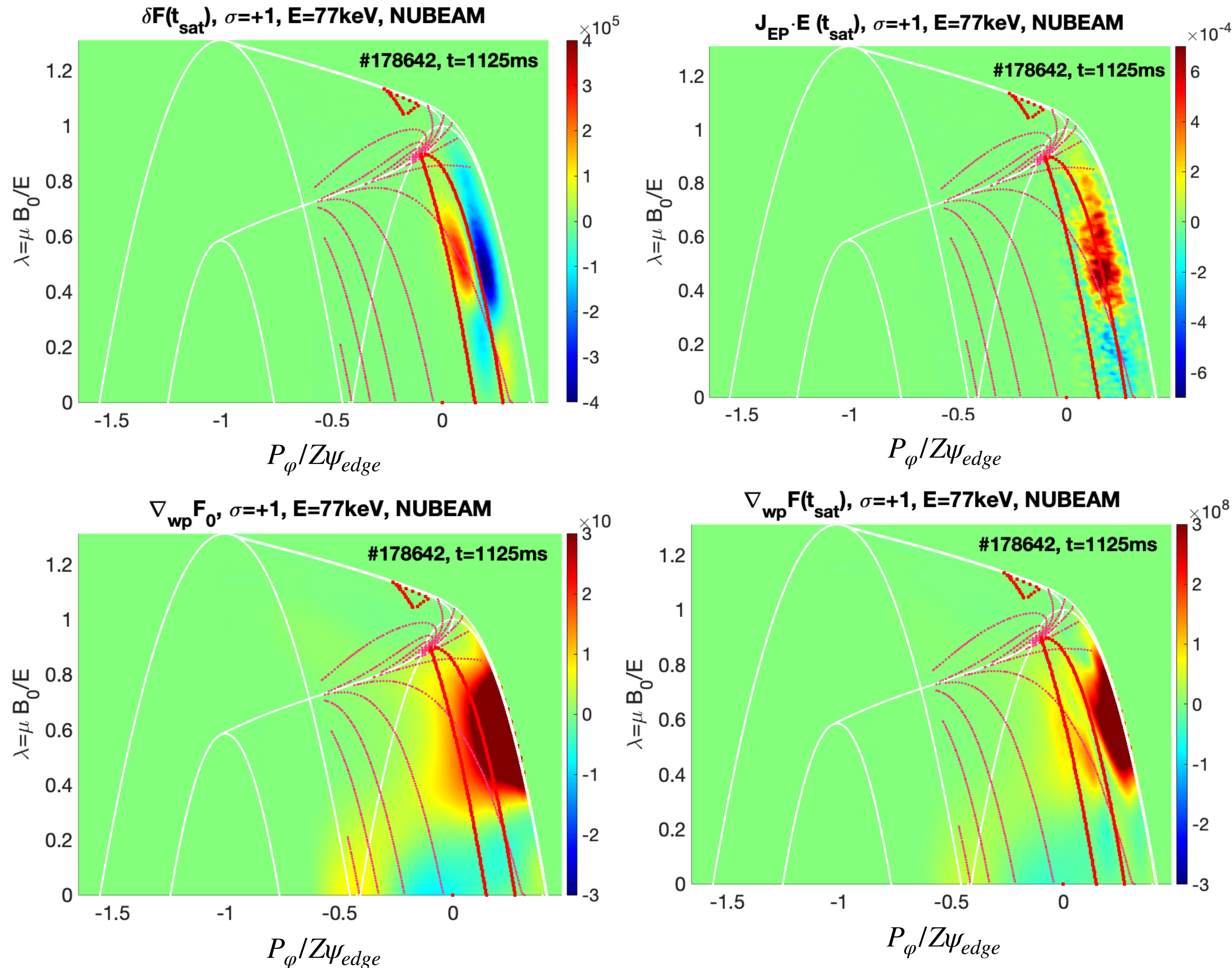
➤ **Current balance** $\mathbf{J}_e(\psi, \theta) = \sum_k \mathbf{J}_k(\psi, \theta) - \nabla \times \mathbf{B} / \mu_0$ is imposed, as anisotropic EP current may be non-negligible

➤ **Isotropic pressure balance** $T_e = (P_{MHD} - \sum_k P_k) / n_e$ 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**



Nonlinear CoM saturation validated by theory



➤ δF_{EP} phase space zonal structures (PSZS [1]) are plotted at BAE saturation

➤ F_{EP} flattening develops around resonances

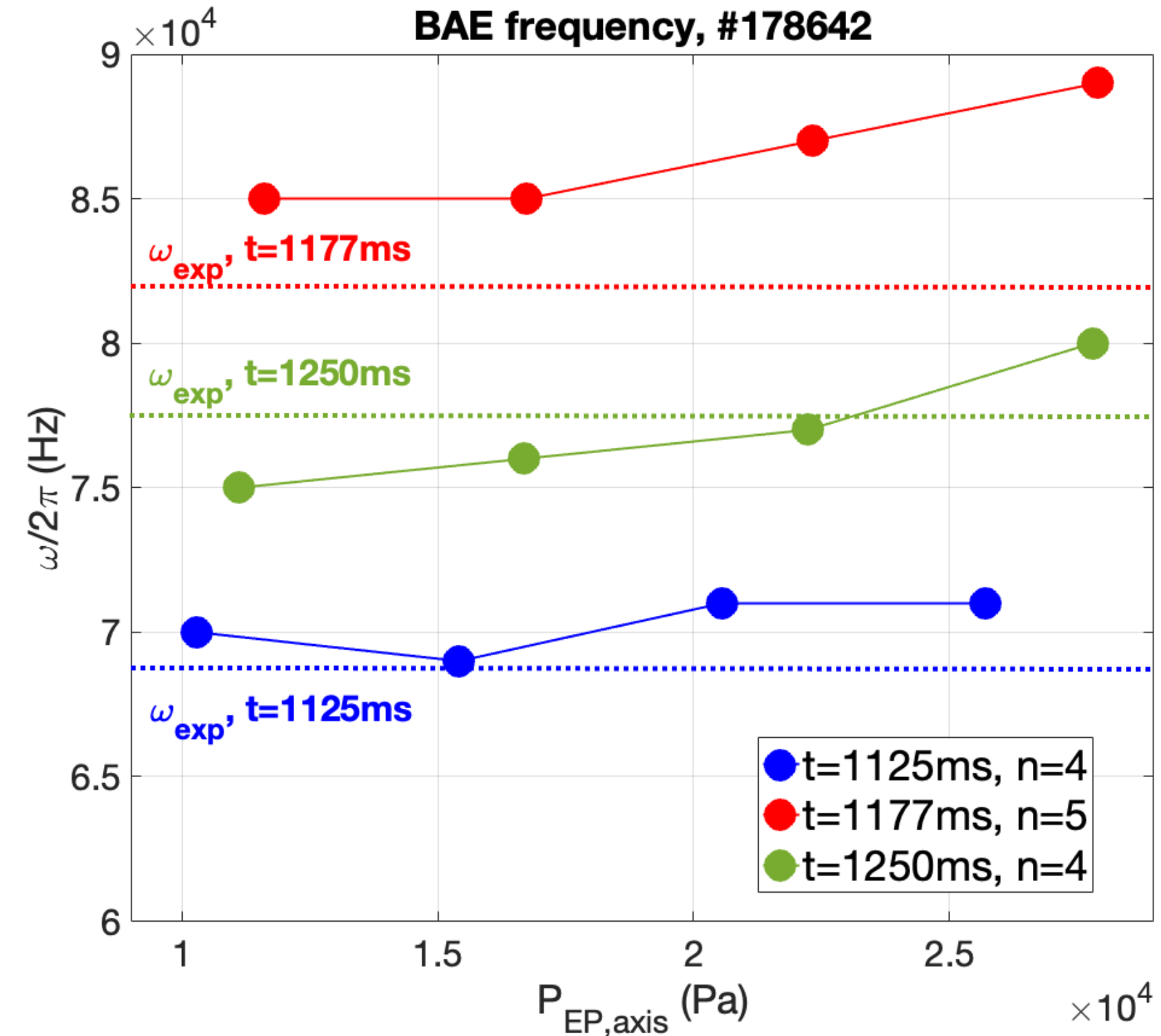
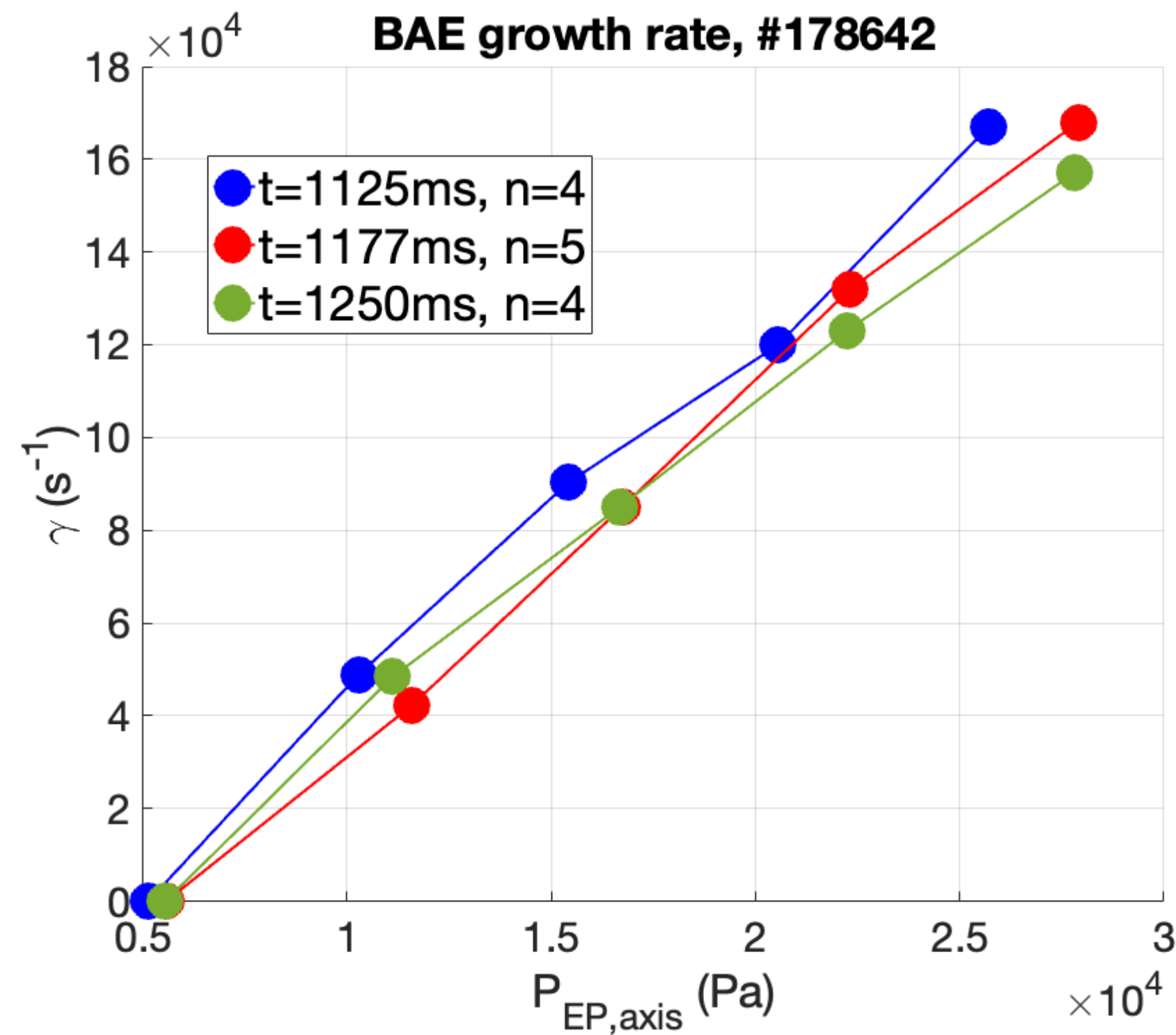
➤ Outward/inward EP transport in GTC consistent with $J_{EP} \cdot E$ and $\nabla_{wp} F_0$ signs

→ GTC CoM version verified theoretically

➤ GTC can be restarted with updated EP distributions, accounting for EP flattening

➤ It provides a direct connection between GTC and the reduced EP transport model ATEP [2]

BAE stability across time slices



- BAE stability is **marginally affected** over the **different times slices** in GTC simulations
- **Contradictory** with **experiment**, where BAEs are stable at t=1177ms
- **Unclear AE nature** at t=1177ms, in laboratory frame $f_{BAE} \sim 130$, $f_{RSAE} \sim 140$ kHz, **both modes peaking near q_{min}**

EP drive and resonances explicit in CoM space

- **EP-driven modes stability** can be described by a **general dispersion relation** [1,2]

$$\omega I_R(\omega) = \delta W_{MHD} + \delta W_{EP}(\omega) \quad \delta W_{EP}(\omega) \propto \frac{n \partial_{P_\phi} F + \omega \partial_E F}{(\omega + p \omega_\theta - n \omega_\phi)}$$

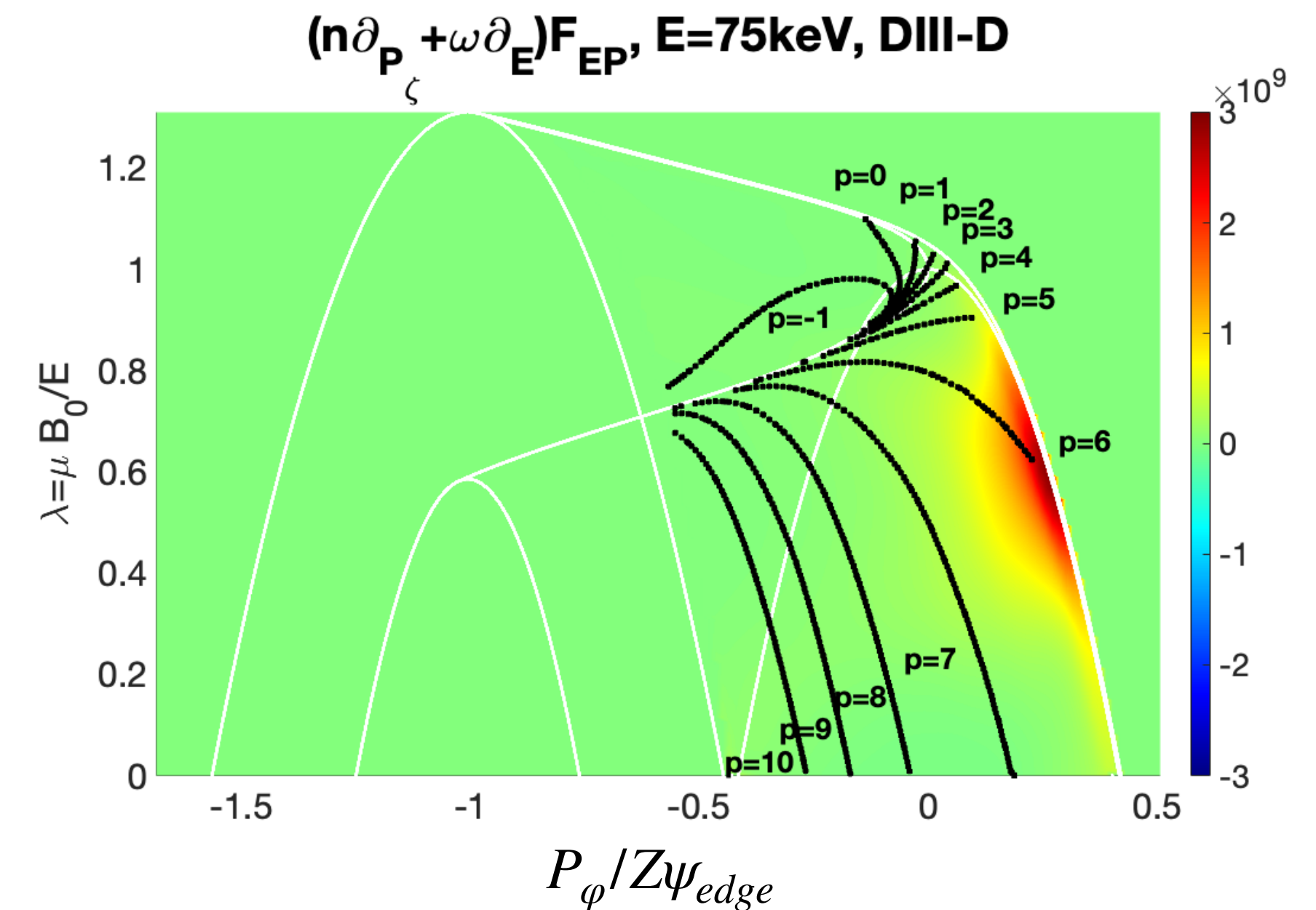
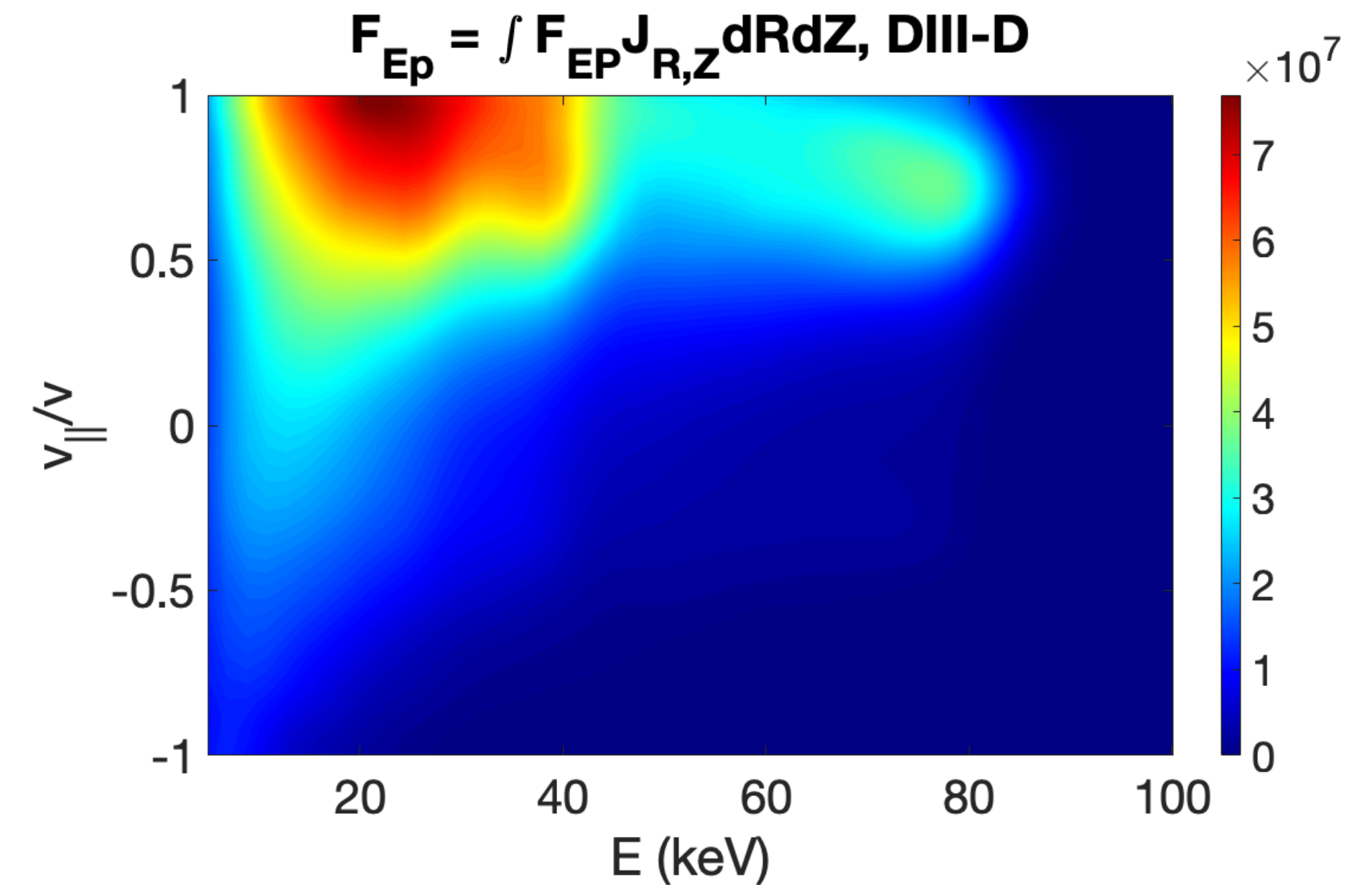
- The sign of $\nabla_{wp} F_0 = n \partial F_0 / \partial P_\phi + \omega \partial F_0 / \partial E$ in **CoM space** determine **stability** of **EP-driven modes**

- ❖ $\nabla_{wp} F_0 > 0 \Rightarrow$ driving instabilities
- ❖ $\nabla_{wp} F_0 < 0 \Rightarrow$ damping instabilities

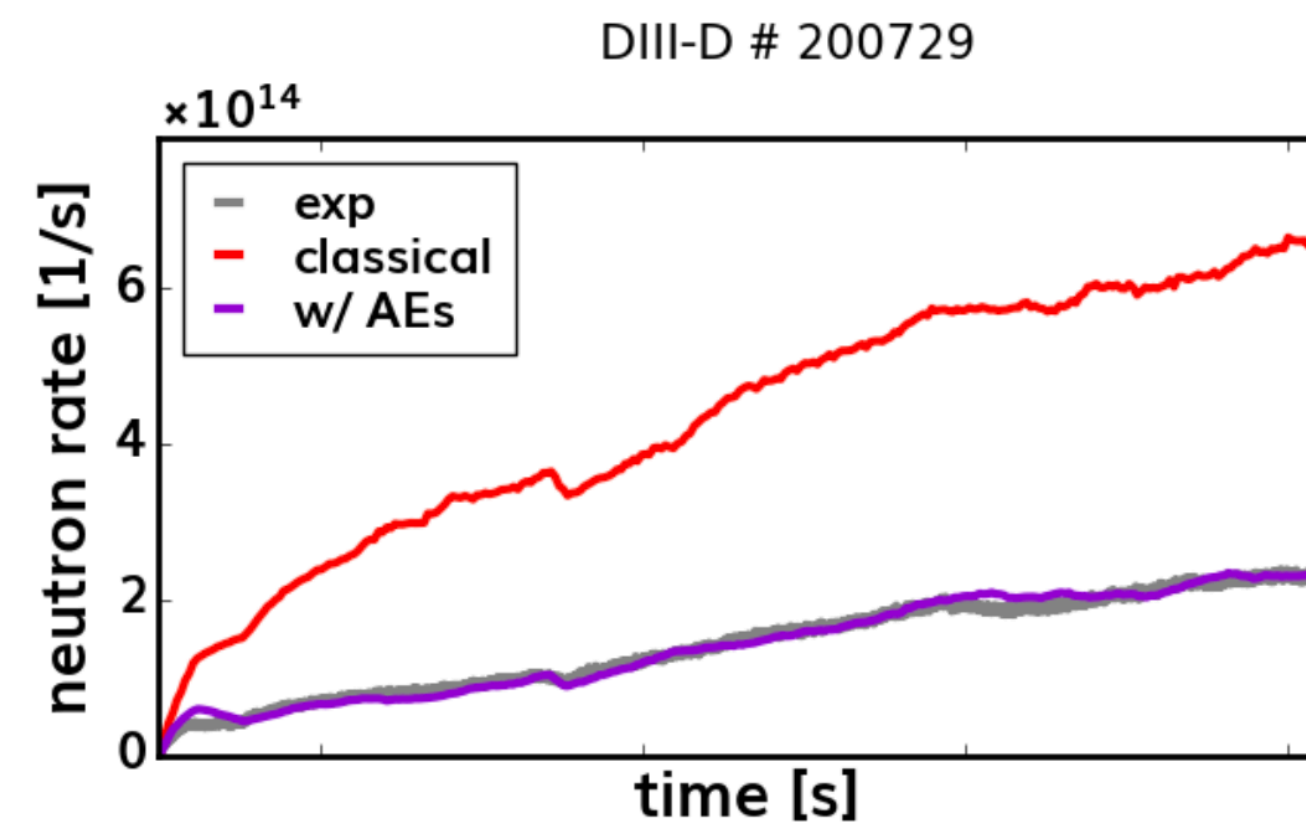
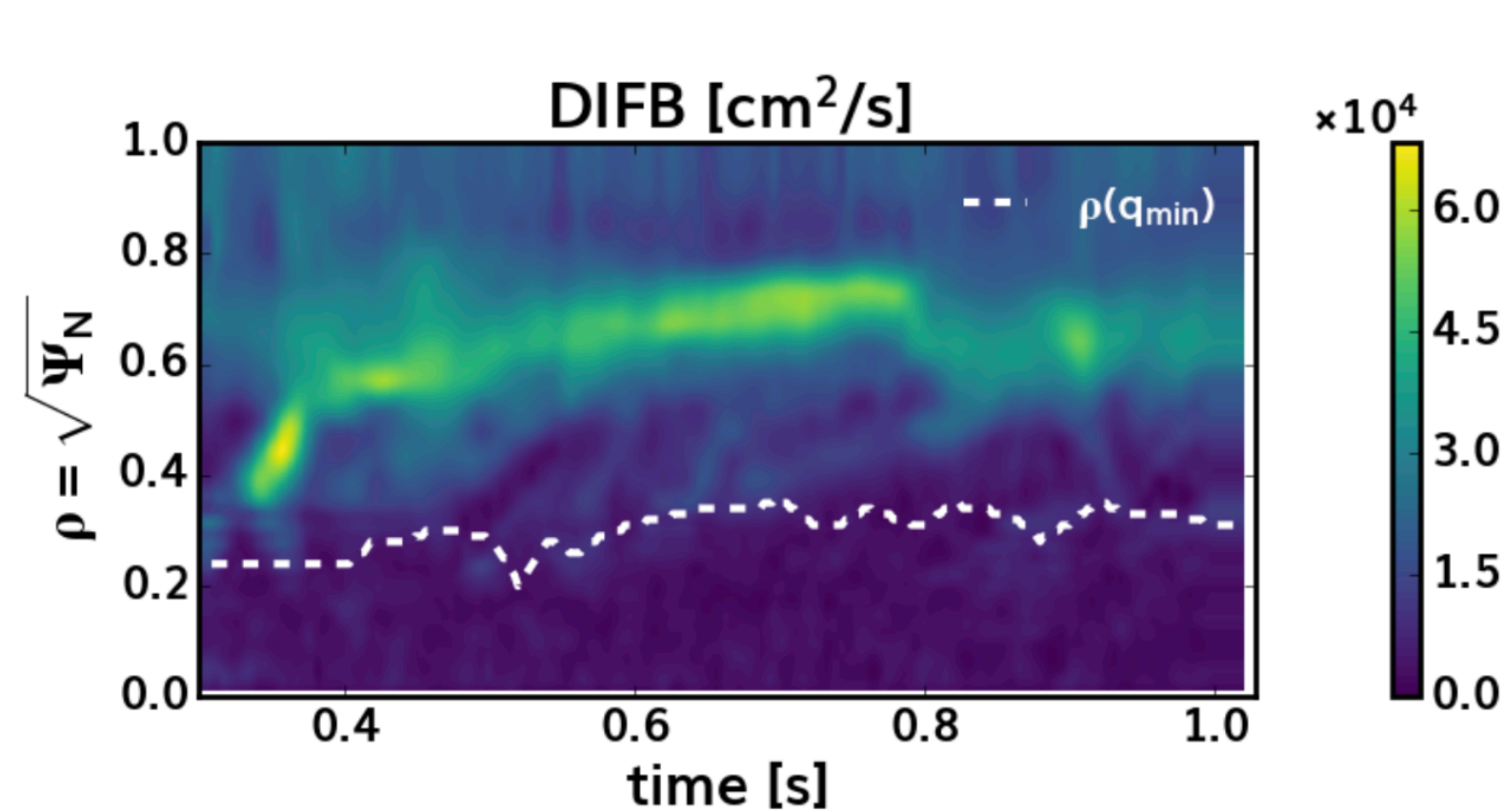
- EP pdf gradients are **driving modes** in the vicinity of **resonances locations** $\omega = n \omega_\phi - p \omega_\theta$, $p \in \mathbb{Z}$

[1] L. Chen et al. 1984, *Phys. Rev. Lett.*

[2] L. Chen and F. Zonca 2016, *Review of Modern Physics*



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

➤ This method is currently applied on #178642, and the new reconstructed beam will be used for validation

