EUROfusion

Mitigation of Alfvén Eigenmodes in Negative Triangularity plasmas at TCV

P. Oyola, M. García-Muñoz, M. Vallar, E. Viezzer, J. Rueda-Rueda, J. Domínguez-Palacios, H. Chen, Y. Todo, S. Sharapov, A. Fasoli, B. Duval, A. Karpoushov, S. Coda, O. Sauter and the TCV and WPTE-RT11 teams.

PSFT Plasma Science and Fusion Technology

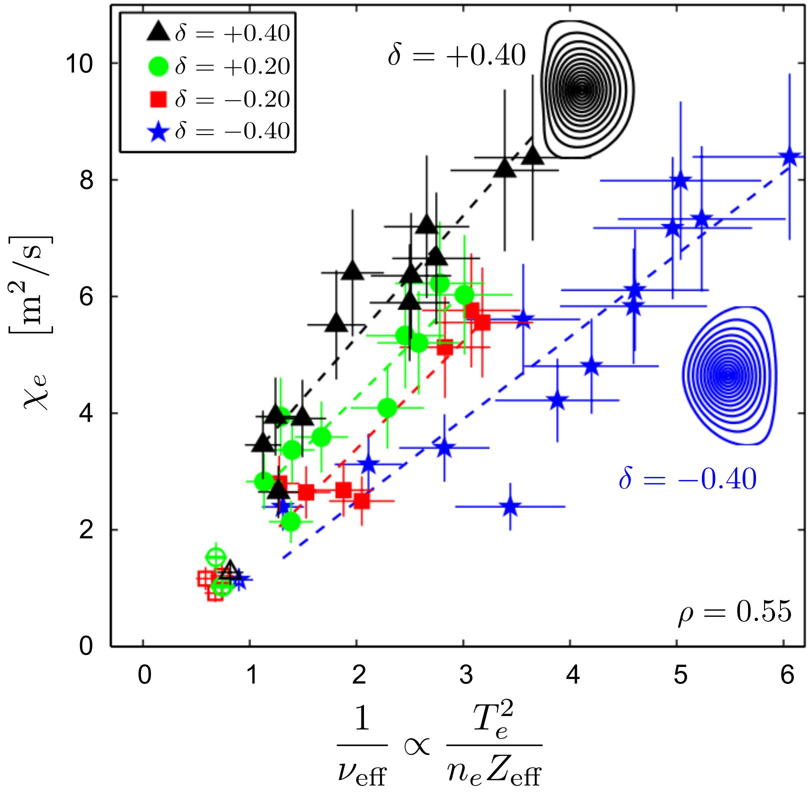
Universidad de Sevilla

EPFL

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

NT as a relevant reactor scenario

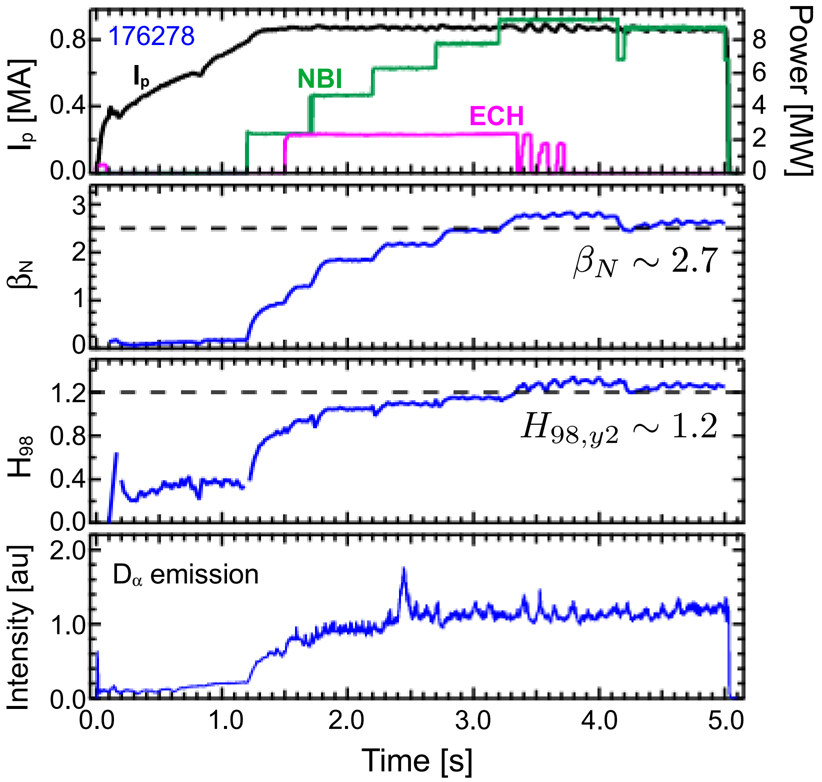
- Strong reduction of electron heat flux in NT was first observed in TCV[1,2].



[1] J. -M. Moret *et al.*, Phys. Rev. Lett. **79** 2057 (1997)
[2] Y. Camenen *et al.*, Nucl. Fusion **47** 510-516 (2007)
[3] M. E. Austin *et al.*, Phys. Rev. Lett. **122** 115001 (2019)

NT is an ELM-free regime with H-mode-like confinement

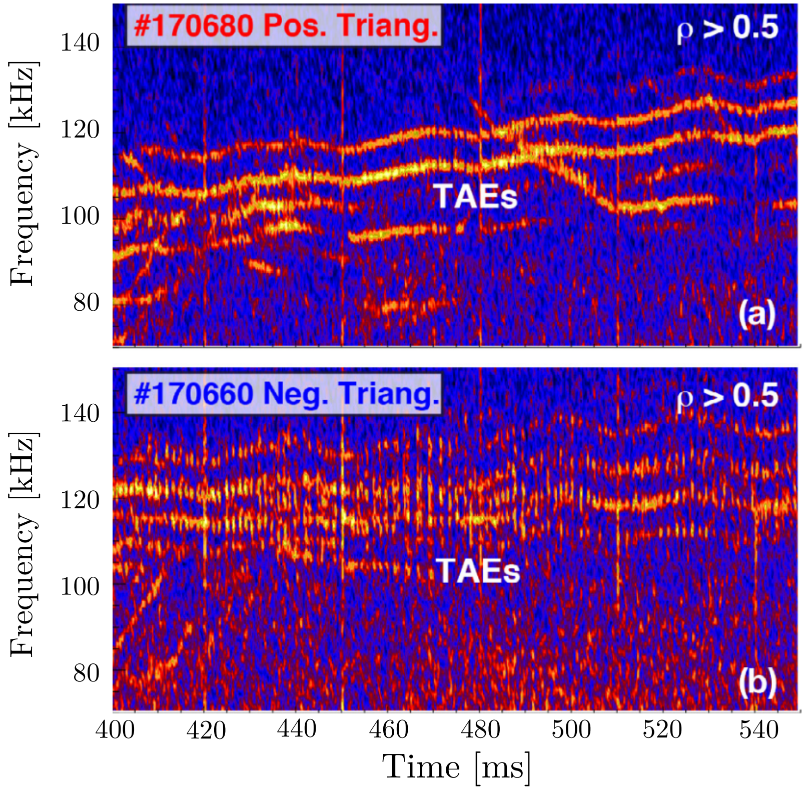
- Strong reduction of electron heat flux in NT was first observed in TCV[1,2].
- DIII-D team first showed that confinement is similar to PT in H-mode[3].
  - H-mode-like confinement in NT L-mode.
  - Natural ELM-free scenario.
- Assessment of AEs and fast-ion transport.



[1] J. -M. Moret *et al.*, Phys. Rev. Lett. **79** 2057 (1997)
[2] Y. Camenen *et al.*, Nucl. Fusion **47** 510-516 (2007)
[3] M. E. Austin *et al.*, Phys. Rev. Lett. **122** 115001 (2019)

AEs in NT firstly observed in DIII-D

- Experiments in DIII-D[4] to obtain AEs, shows TAEs excited in NT and PT.

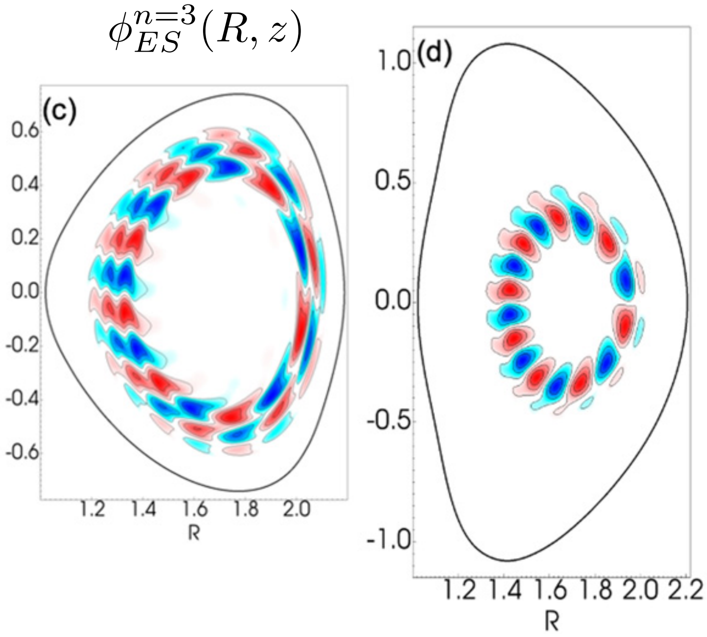


[4] M. A. Van Zeeland *et al.*, NF **59** 086028 (2019)
[5] Y. Ghai *et al.*, NF **61** 126020 (2021)
[6] L. A. Charlton *et al.*, J. Comp. Phys **86** 270 (1990)

Gyrofluid simulations indicate negligible impact on AE activity

- Experiments in DIII-D[4] to obtain AEs, shows TAEs excited in NT and PT.

- Numerical studies[5] with FAR3d[6]:
  - Linear EP-driven AE.
  - 2-moments gyrofluid model for FI
  - Negligible impact of triangularity on AE growth rate



See talk by Y. Ghai on Monday

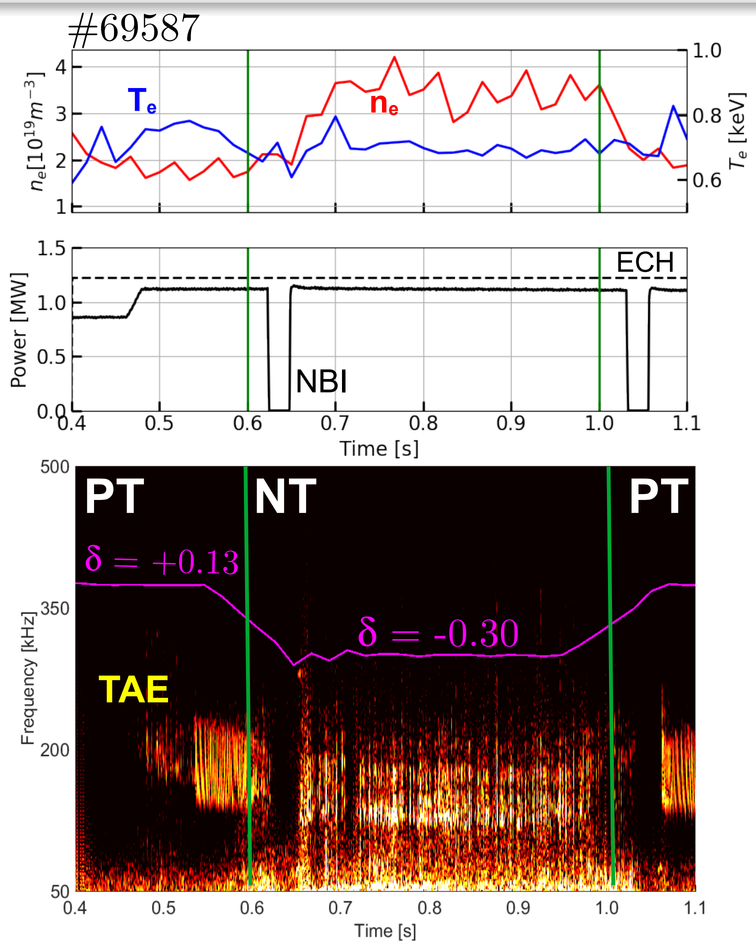
[4] M. A. Van Zeeland *et al.*, NF **59** 086028 (2019)
[5] Y. Ghai *et al.*, NF **61** 126020 (2021)
[6] L. A. Charlton *et al.*, J. Comp. Phys **86** 270 (1990)

Strong NT impact on AEs at TCV

- In experiments, triangularities has a strong impact on observed NBI-driven TAEs:
  - In NT, TAEs appear with lower frequency and amplitude.

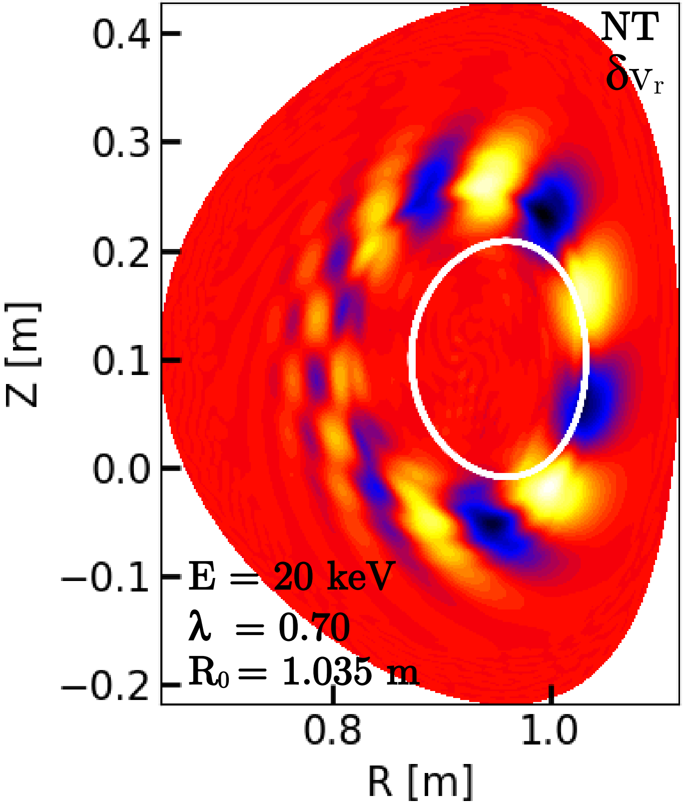
- Uncontrolled changes in many variables:
  - Density rise during NT phase (better confinement)
  - *q*-profile
    - → Direct comparison between triangularities is difficult.

- Simulations needed to assess and isolate triangularity impact on modes evolution and FI transport.



Outline

- MEGA: 3D nonlinear hybrid kinetic-MHD
- Simulation setup for TCV
- TAEs in NT and PT
- Wave-particle resonances in the FI phase-space
- Fast-ion losses induced by TAE in NT and PT



MEGA[7]: Nonlinear 3D hybrid kinetic-MHD code

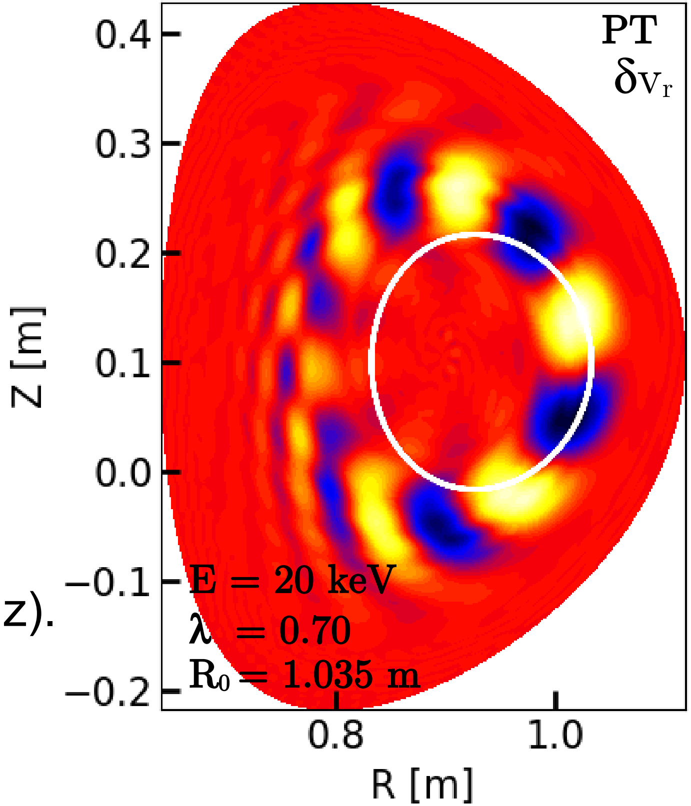
Bulk plasma

- Full resistive-MHD model.

Coupling through current density

Fast-ions

- *Particle-in-cell*: markers sampling distribution function.
- Gyrokinetic equation (δf or *full*-f).



- 4th order finite differences in **cylindrical** coordinates (R, ϕ, z).
- Explicit 4th Runge-Kutta for time-integration.

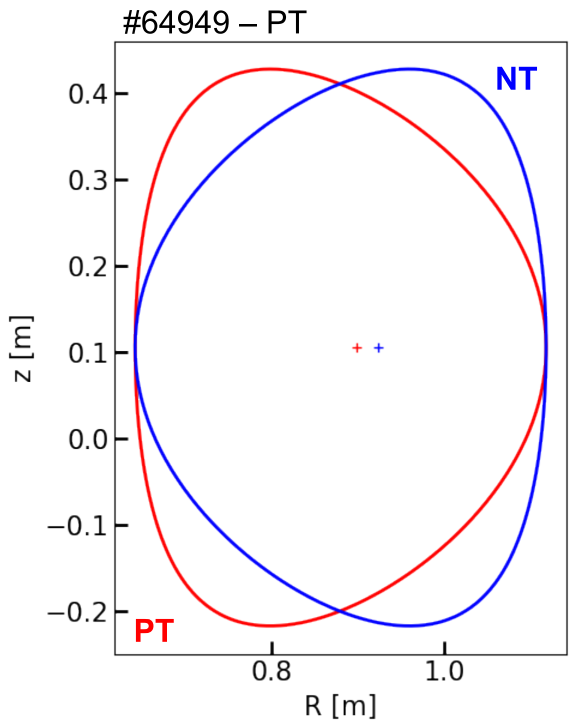
[7] Y. Todo *et al.*, PoP **5** 1321 (1998)

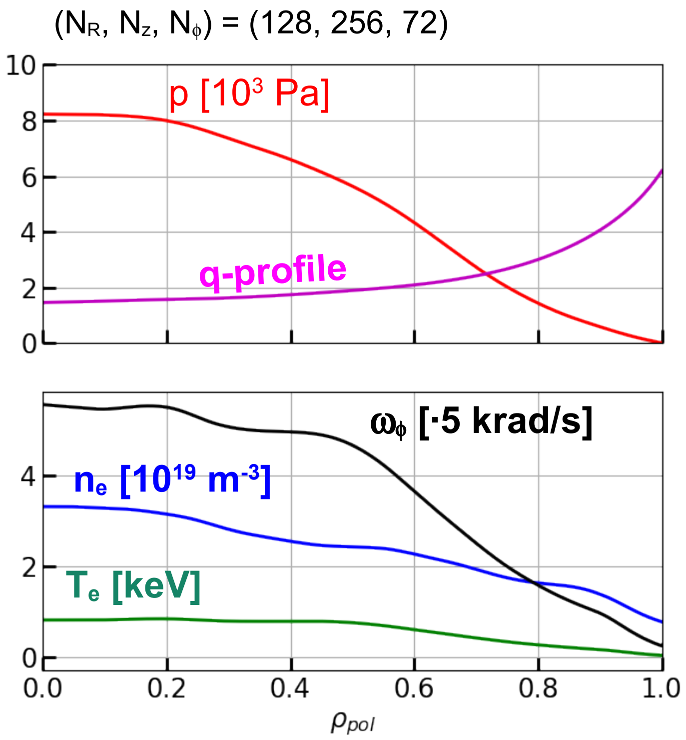
Simulation setup for the δ comparison

- Flipped equilibrium to isolate the +δ / -δ effects on AE activity.

Simulation parameters

- δf-method for kinetic species.
- #markers = 23M particles
- Multi-*n* simulation (n < 5)



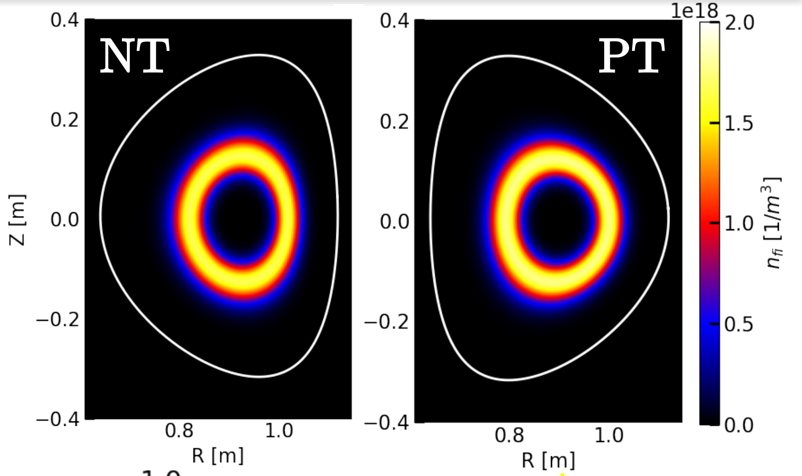


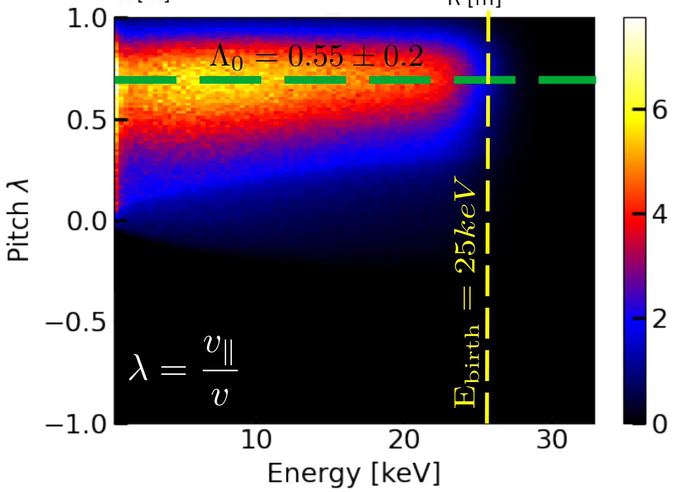
Ad-hoc initial FI distribution

Analytical anisotropic slowing-down distribution

$$f_0 \propto e^{\frac{(\rho-\rho_0)^2}{2(\Delta\rho_0)^2}} \frac{1}{v^3 + v_{crit}^3} erfc\left(\frac{v - v_{birth}}{\Delta v}\right) e^{\frac{(\Lambda-\Lambda_0)^2}{2(\Delta\Lambda)^2}}$$

- Scan in different pitch-angle injections $\Lambda_0 \equiv \frac{\mu B_{\text{axis}}}{E}$
- Scan in different fast-ion gradient location ρ_0





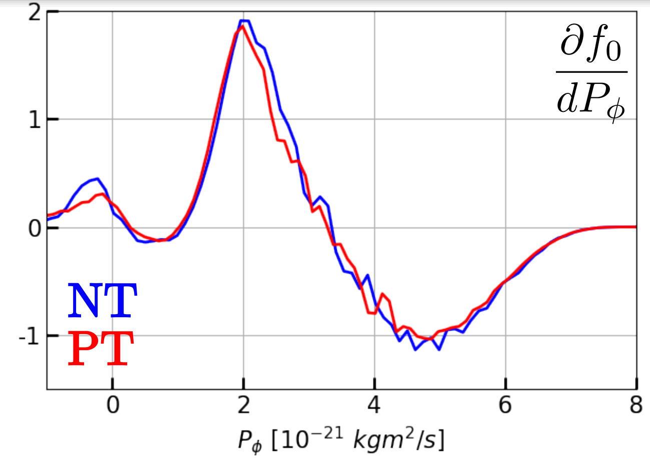
Initial FI drive is the same for NT and PT

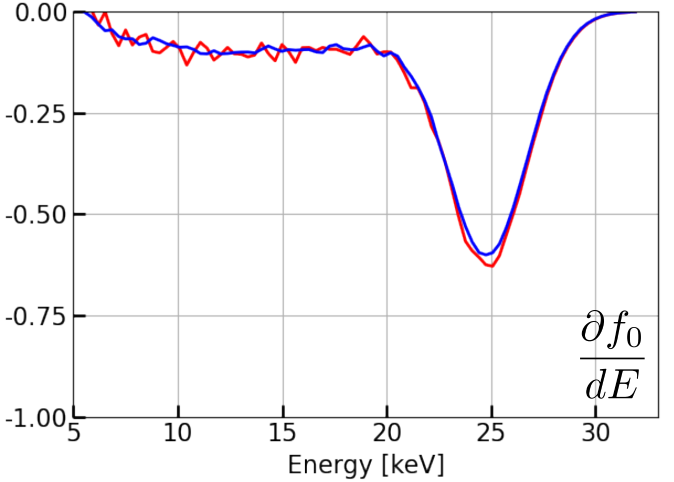
Analytical slowing-down distribution:

$$f_0 \propto e^{\frac{(\rho-\rho_0)^2}{2(\Delta\rho_0)^2}} \frac{1}{v^3 + v_{crit}^3} erfc\left(\frac{v - v_{birth}}{\Delta v}\right) e^{\frac{(\Lambda-\Lambda_0)^2}{2(\Delta\Lambda)^2}}$$

- Scan in different pitch-angle injections $\Lambda_0 \equiv \frac{\mu B_{\text{axis}}}{E}$
- Scan in different fast-ion gradient location ρ_0

$$\gamma_{TAE} \propto \beta_{FI}\left(\frac{\partial f_0}{\partial E} + \frac{n}{\omega}\frac{\partial f_0}{\partial P_\phi}\right)$$

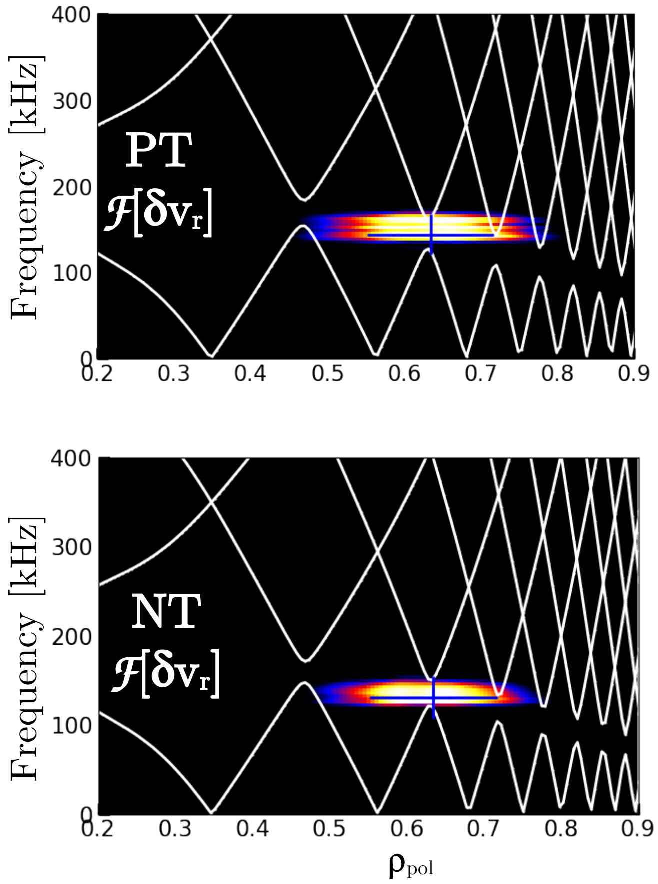




TAEs are obtained in MEGA for PT and NT

TAEs appear both in PT and NT:

- SAW continuum not affected by different Shafranov shifts in NT vs. PT.



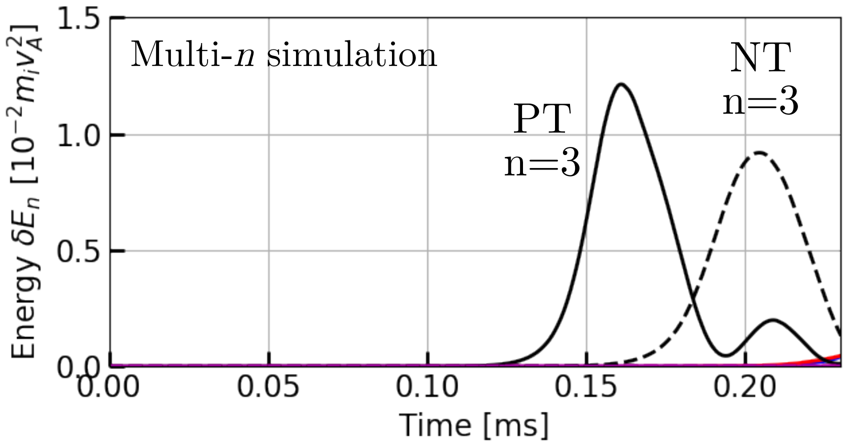
TAEs is mitigated in NT vs PT

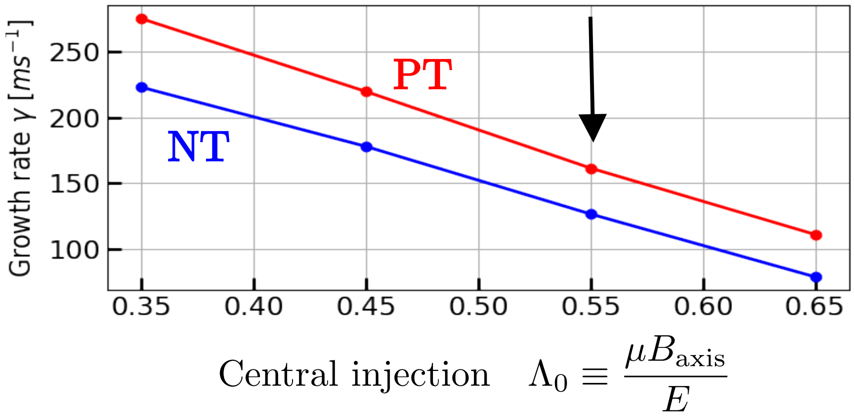
TAEs appear both in PT and NT:

- PT reaches an energy ~50% higher.

- NT shows a smaller growth rate.

- This trend is kept independent on the pair of parameters Λ_0 and ρ_0.





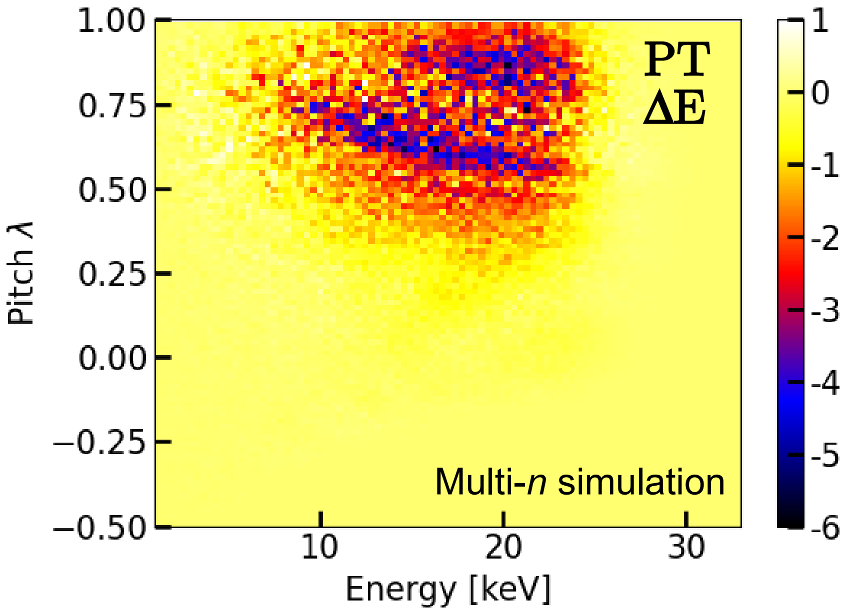
Resonant energy exchange in FI phase-space

- Power exchange in FI phase-space shows particle-wave resonances.

$$\Delta E > 0 \longrightarrow \text{Energy to the FI}$$

$$\Delta E < 0 \longrightarrow \text{Energy to the wave}$$

- Two main regions of the phase-space providing energy to TAE.



Resonant energy exchange in FI phase-space

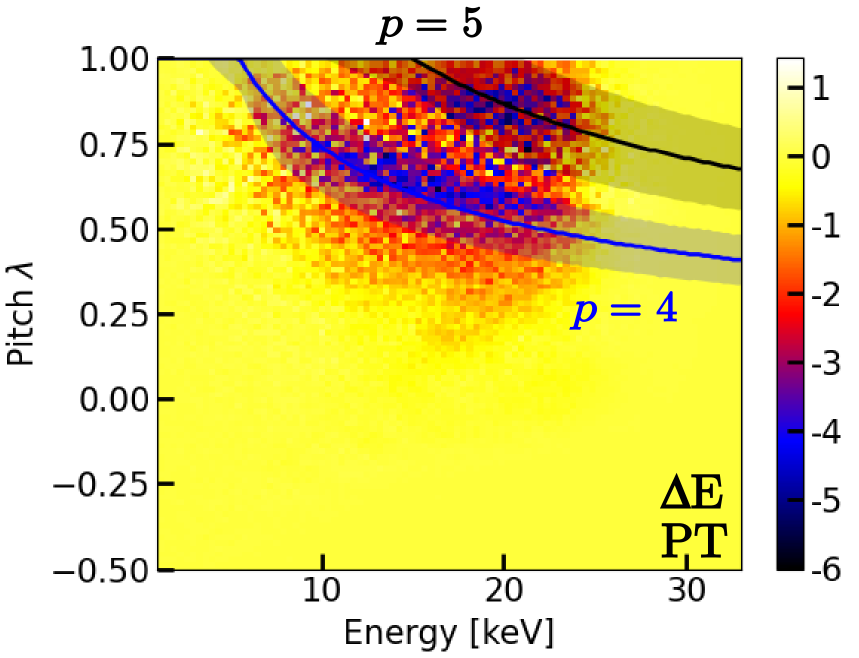
- Power exchange in FI phase-space shows particle-wave resonances.

$$\Delta E > 0 \longrightarrow \text{Energy to the FI}$$

$$\Delta E < 0 \longrightarrow \text{Energy to the wave}$$

- Two main regions of the phase-space providing energy to TAE:
  - Wave-particle resonances[8].

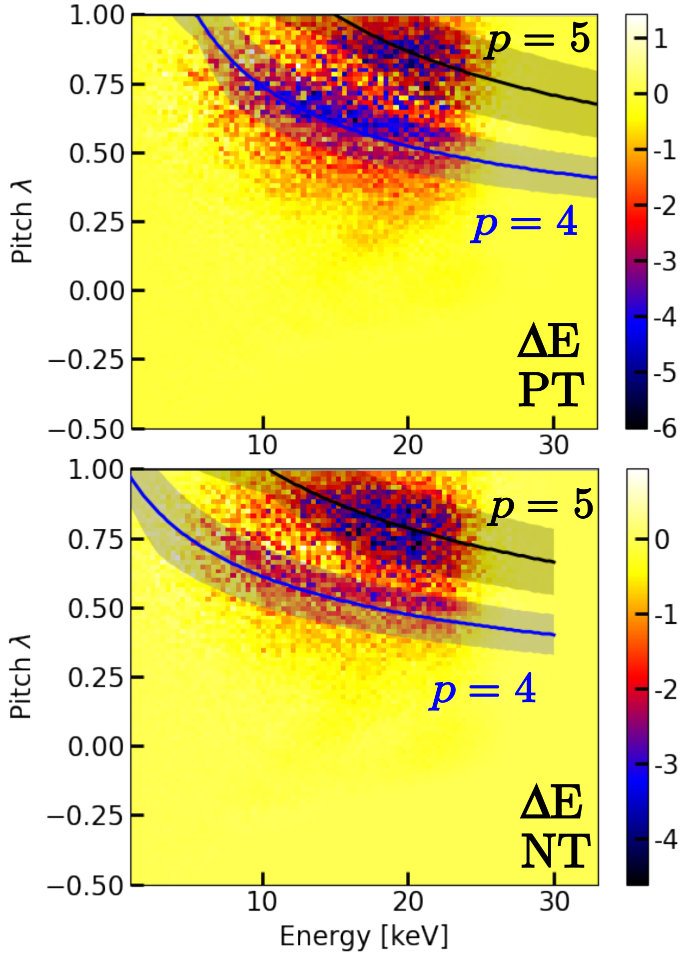
$$\omega_{\mathrm{TAE}} = n\omega_\phi - p\omega_{\mathrm{pol}}$$



[8] Y. Todo, Rev. Mod. Plasma Phys **3**, 1 (2019)

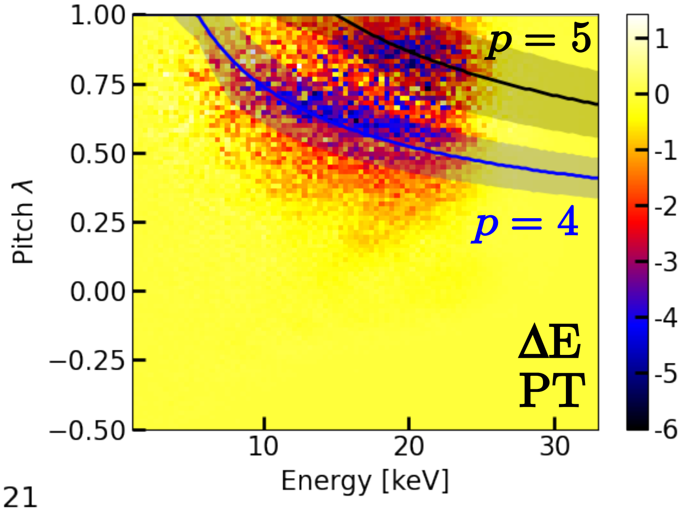
NT damps the lower bounce harmonic

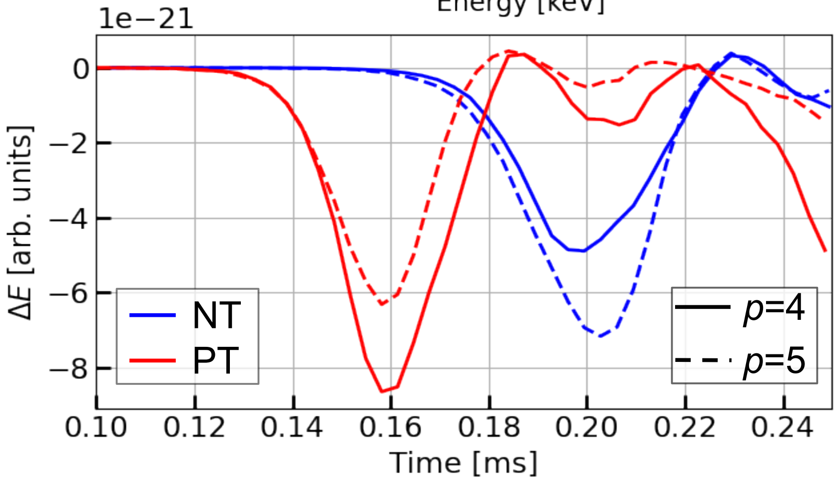
- Alignment of analytical resonances with structures in FI phase-space.
- In PT, lower bounce harmonic is most excited.
- In NT, damps lower bounce harmonics.



NT damps the lower bounce harmonic.

- Alignment of analytical resonances with structures in FI phase-space.
- In PT, lower bounce harmonic is most excited.
- In NT, damps lower bounce harmonics.
- Overall energy transfer is larger in PT.



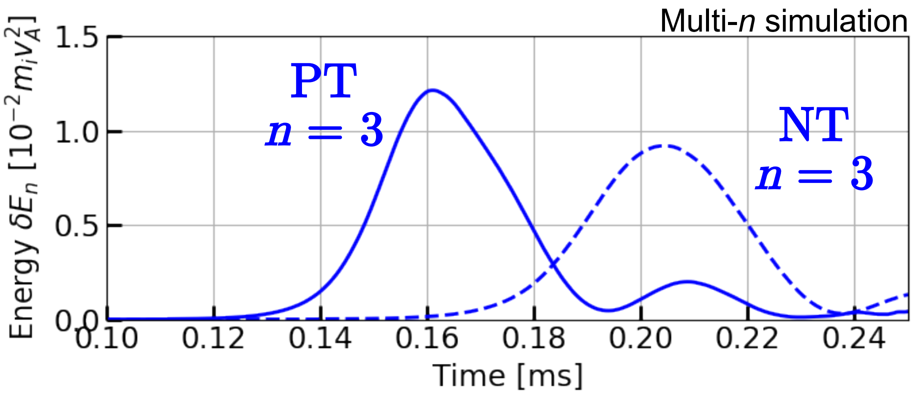


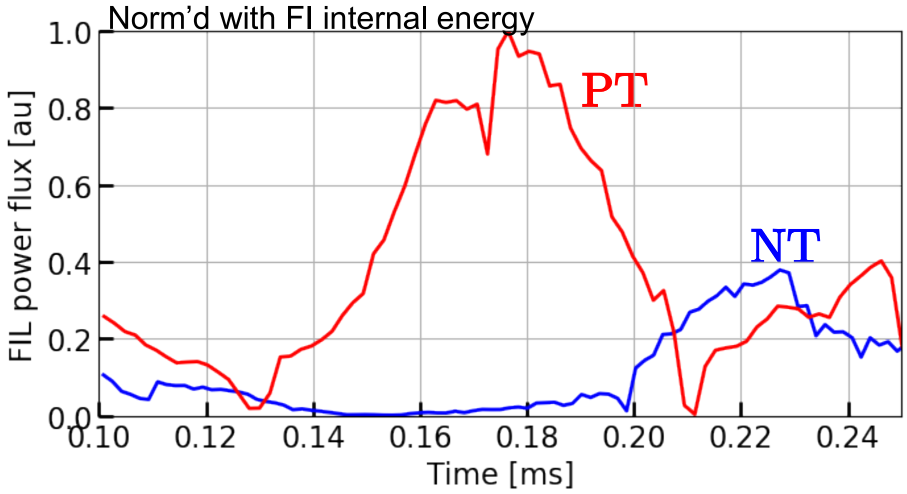
TAE-induced FIL are 3x lower in NT

- Fast-ion losses in NT is **smaller** than its counterpart in PT.
  - 3x times lower at the peak.
  - 3x times lower integrated FIL.

- Correlated FIL bursts with TAE saturation.

- Single-*n* simulations shows similar results for a *n*=3 TAE.





Conclusions

- In experiments, TAEs appear weaker in NT than in its counterpart PT.
- MEGA sims used to isolate the δ effects.
- 50% lower energy in NT with respect to PT.
- Lower bounce harmonics are damped in NT.
- Fast-ion losses are 3x lower in NT.