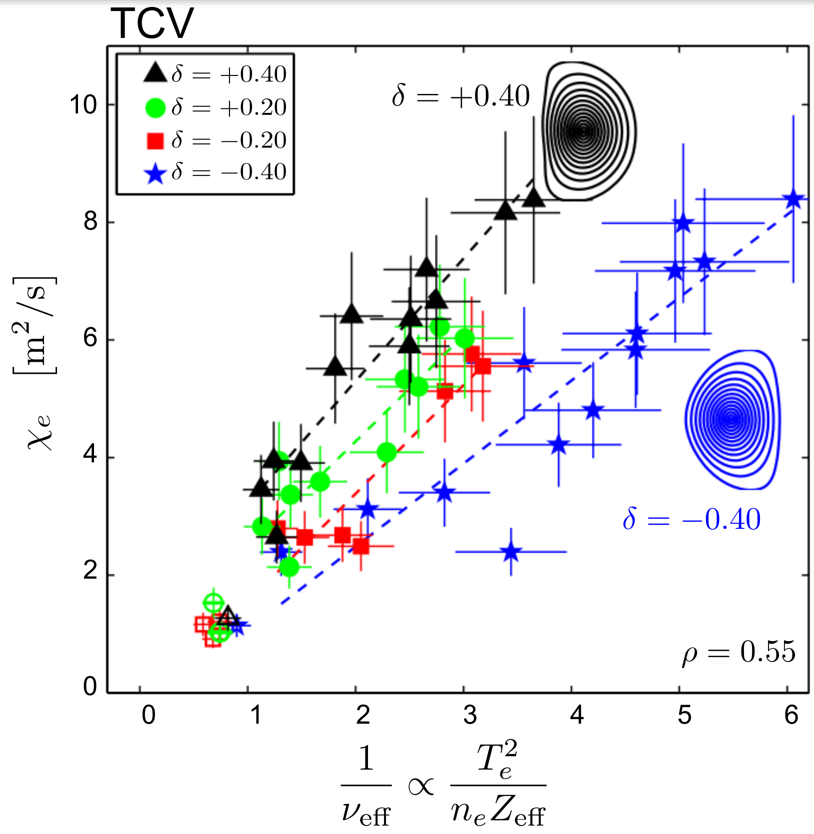
Mitigation of Alfvén Eigenmodes in Negative Triangularity plasmas at TCV

P. Oyola, M. García-Muñoz, M. Vallar, E. Viezzer, J. Rueda-Rueda, J. Domínguez-Palacios, A. Fasoli, B. Duval, M. Dreval, A. N. Karpushov, S. Coda, O. Sauter, J. Poley-Sanjuan, J. Gonzalez-Martin, D. J. Cruz-Zabala, Y. Todo, K. Särkimäki, and the TCV and EUROfusion tokamak Exploitation teams.

This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

NT emerges as a promising reactor scenario

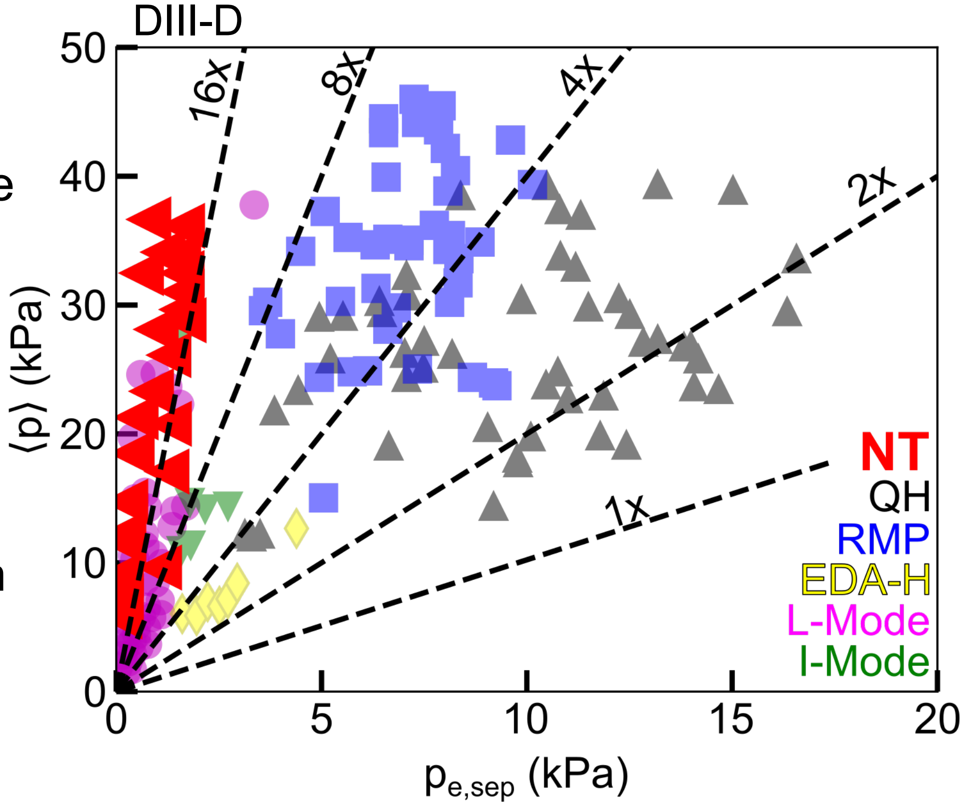
- Improved confinement
  - Reduced turbulence level[1]



[1] Y. Camenen *et al*., Nucl. Fusion **47** 510-516 (2007)

NT emerges as a promising reactor scenario

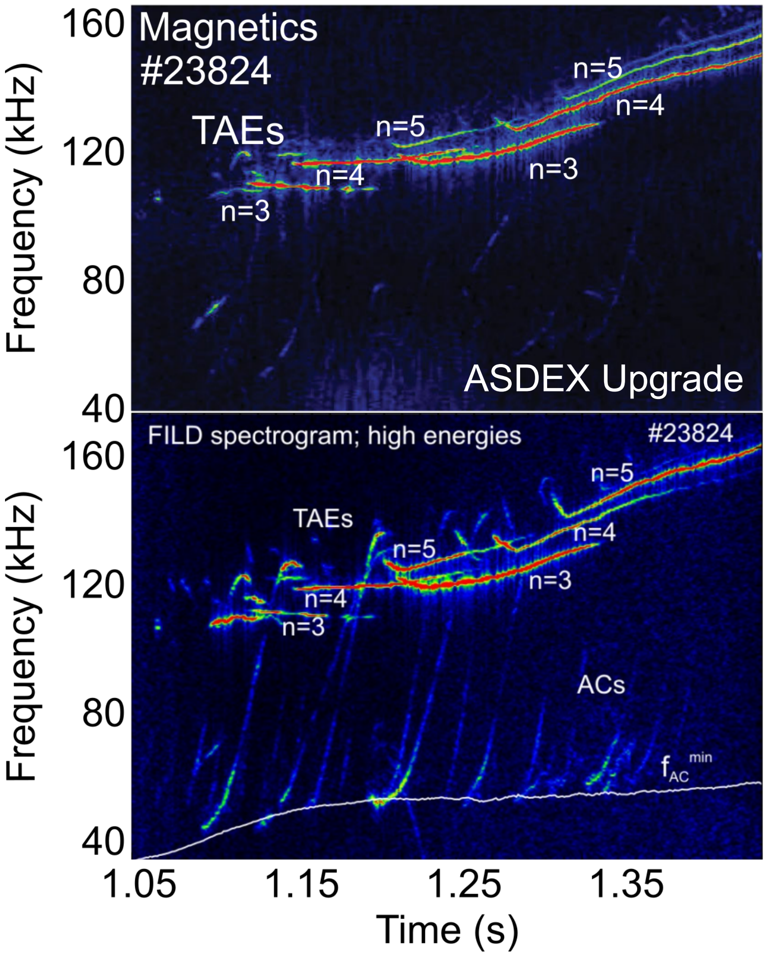
- Improved confinement
  - Reduced turbulence level
- High plasma performance and naturally ELM-free
  - Reduced heat loads on the wall
- Divertor at larger radius
  - Larger wetted area
  - Easier integration
- Fast-ion behaviour and associated fluctuations in NT plasma?



Adapted from C. Paz-Soldan *et al*, PPCF (2021)

Fast-ions are the main source of energy and momentum

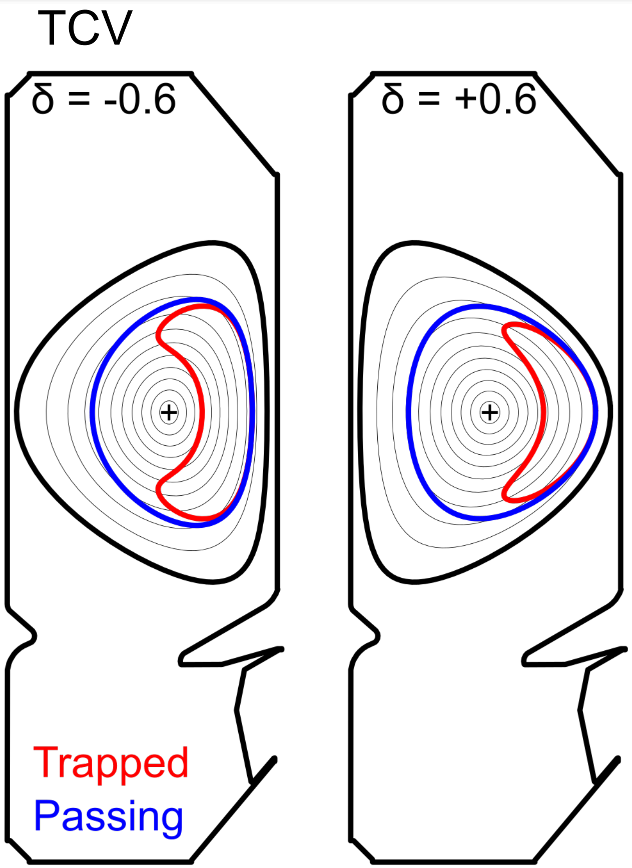
- Fast-ions are key for a successful fusion reactor:
  - Heating and current drive
  - Avoid damages to the Plasma Facing Components
- Fast-ions are subject to transport by a variety of instabilities:
  - AEs are a prominent source of anomalous transport[2]



[2]M. Garcia-Munoz *et al*., Phys. Rev. Lett. **104** (2010)

NT may have a significant impact on the fast-ions and the associated fluctuations

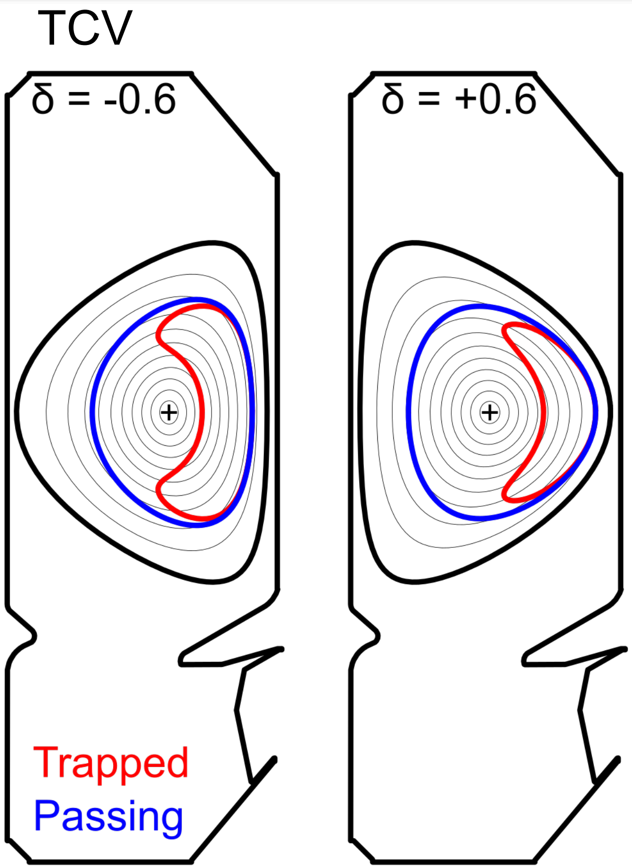
- Changes in the magnetic topology translate into changes in the orbit topology
  - Orbit topology impact on fast-ion – fluctuations interactions



*Synthetic equilibria

NT may have a significant impact on the fast-ions and the associated fluctuations

- Changes in the magnetic topology translate into changes in the orbit topology
  - Orbit topology impact on fast-ion – fluctuations interactions
- Changes in the plasma shape also impact on the MHD fluctuations
  - Differences in the Shafranov shift[3]
  - Improved kinetic profiles in NT

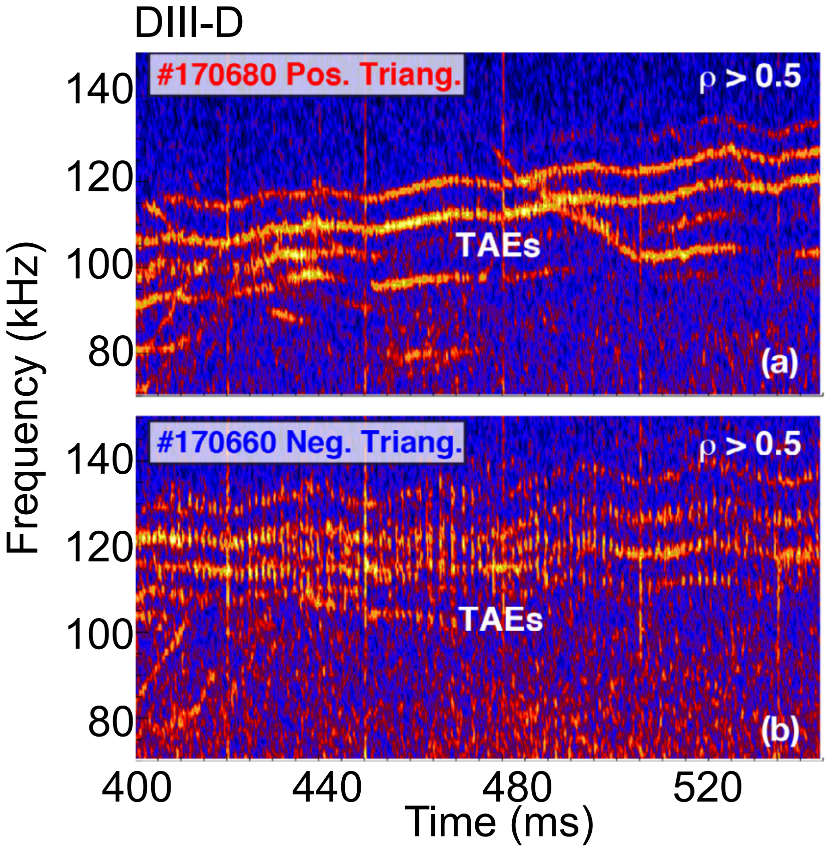


[3]J. P. Graves, PPCF (2013)

*Synthetic equilibria

TAEs first excited in NT plasmas at DIII-D

- DIII-D team was the first one able to excite TAEs in NT plasmas[4,5]
  - Slight impact on the AE activity.

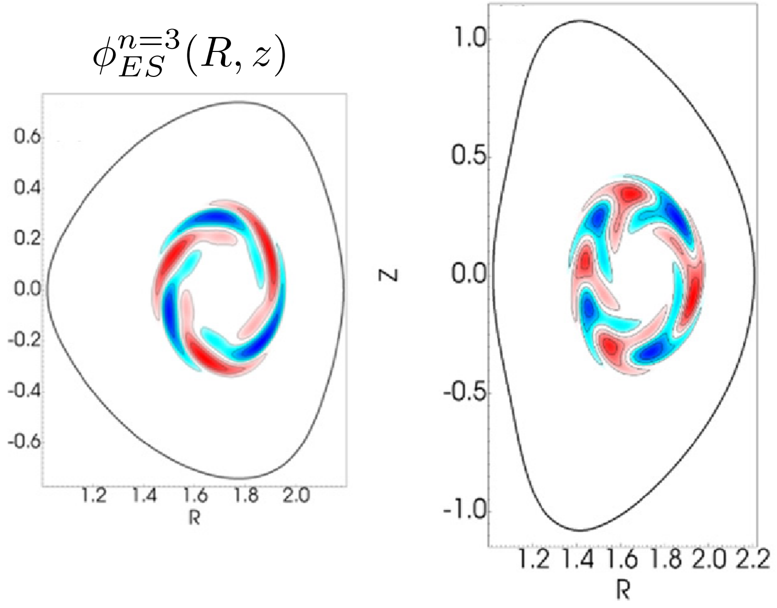


[4] M. A. Van Zeeland *et al.*, 15th IAEA TM on EP (2017)
[5] M. A. Van Zeeland *et al.*, NF **59** 086028 (2019)

Gyrofluid simulations indicate negligible impact on AE activity

- DIII-D team was the first one able to excite TAEs in NT plasmas

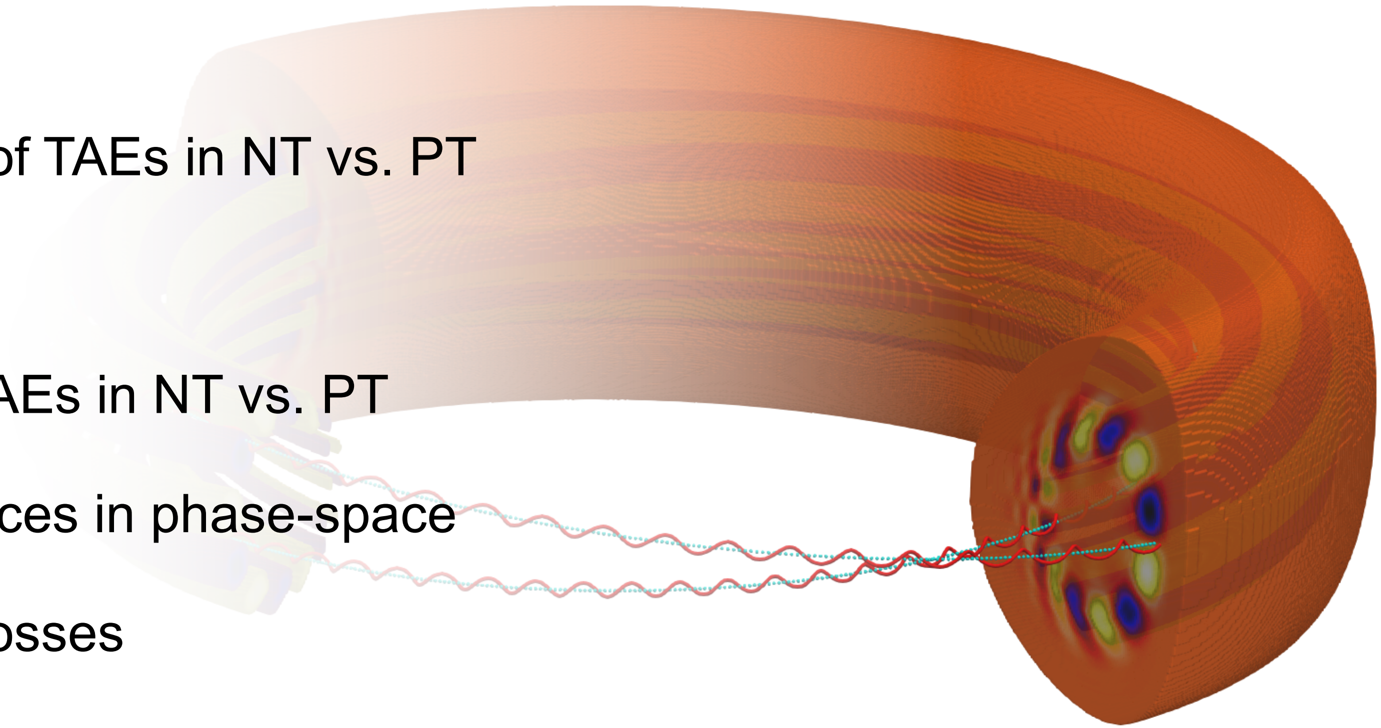
- Numerical studies[6] with FAR3d[7]:
  - Linear EP-driven AE
  - 2-moments gyrofluid model for FI
  - Negligible impact of triangularity on AE growth rate



[6] Y. Ghai *et al.*, NF **61** 126020 (2021)
[7] L. A. Charlton *et al.*, J. Comp. Phys **86** 270 (1990)

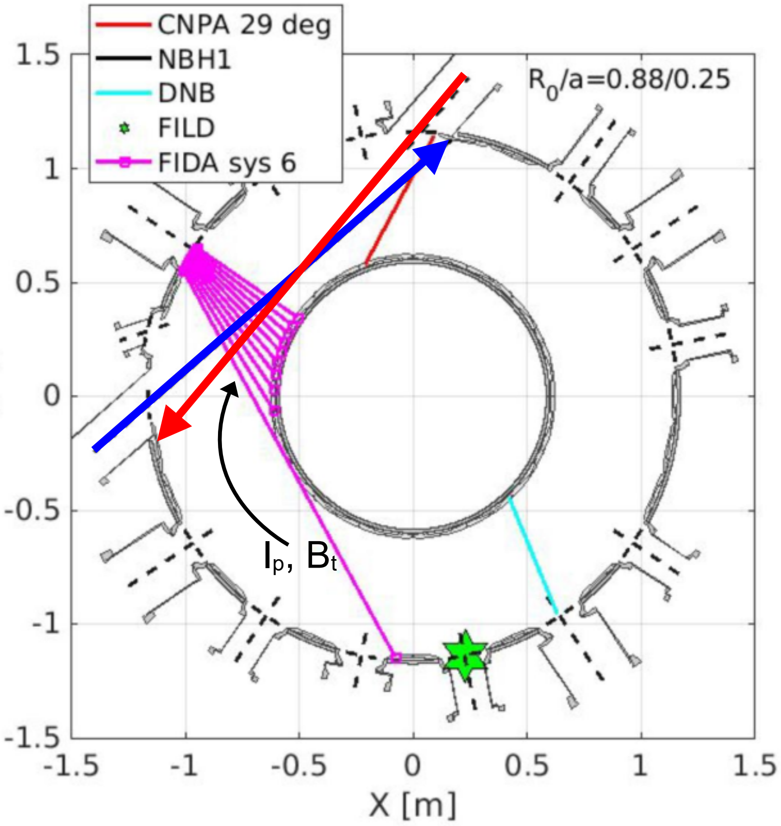
Outline

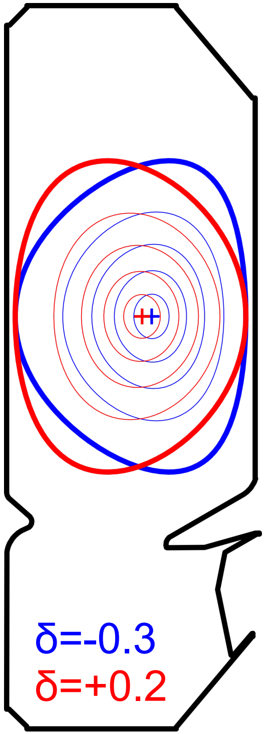
- NT experiments at TCV
- Hybrid kinetic modeling of TAEs in NT vs. PT
  - MEGA
  - Overall behaviour of TAEs in NT vs. PT
  - Wave-particle resonances in phase-space
  - TAE-induced fast-ion losses
- Conclusions



TCV is an ideal testbed due to its flexible shaping and heating and diagnostic capabilities[8]

- Large ranges of shapes can be achieved:
  - $\delta \in (-0.8, +0.9)$
  - Can be varied in real-time
- A variety of heating systems:
  - Neutral Beam Injection (NBI)
    - Co-going injection @ 25 keV
    - Counter-going injection @ 60 keV
  - Electron Cyclotron Heating (ECH)
    - 5 gyrotrons up to 3.5 MW

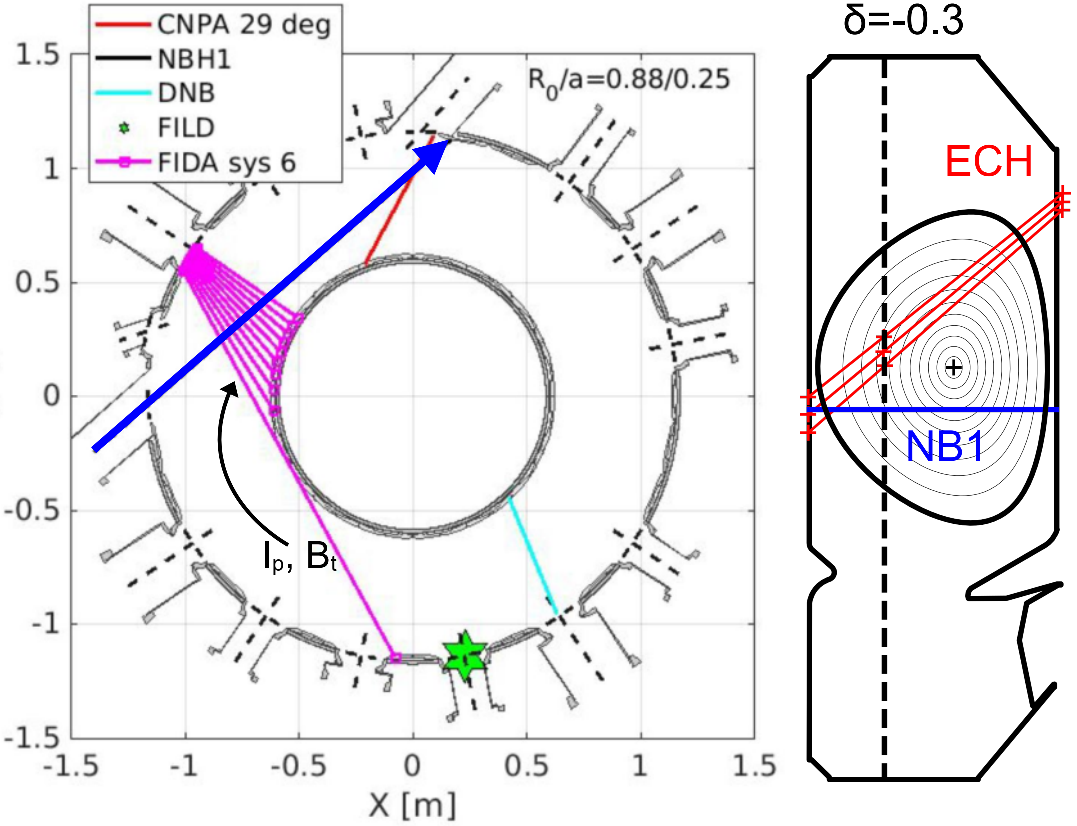




[8]H. Reimerdes *et al.*, NF **62** (2022)

Off-axis NBI heating excites TAEs at TCV

- L-mode plasma with B_t=+1.3T and co-going I_p=+130 kA
- NBI-1 injection @ **25 keV**
  - Off-axis injection to excite AEs
  - Early NBI injection for an elevated *q*-profile
  - NBI power at 1.3 MW
- **0.6 MW ECH power**
  - lower collisionality
  - larger fast-ion content

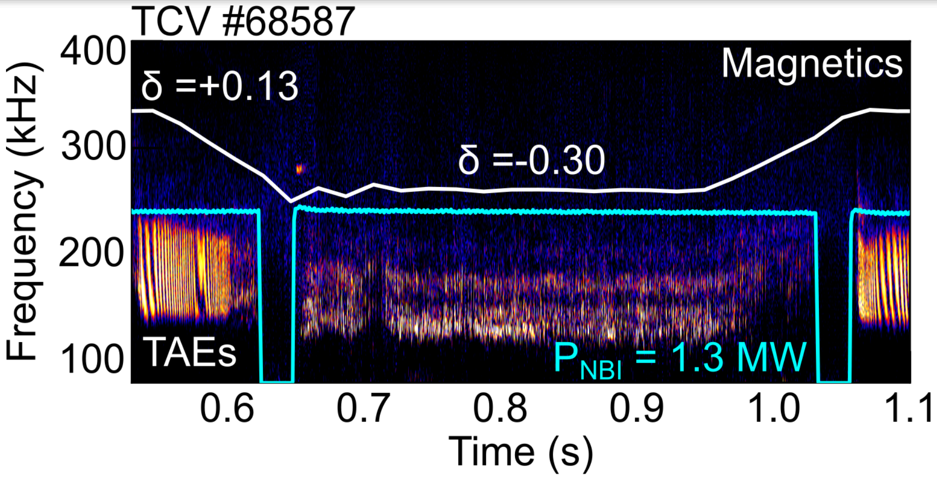


A. N. Karpushov *et al.*, EPS 2023

Experiments show strong NT impact on AEs

- Triangularity real-time scan modifies AE activity:
  - Clear EP-drive nature
  - Reduced amplitude ~ 50 %

- Plasma shaping also has an impact on the overall plasma quantities:
  - *q*-profile

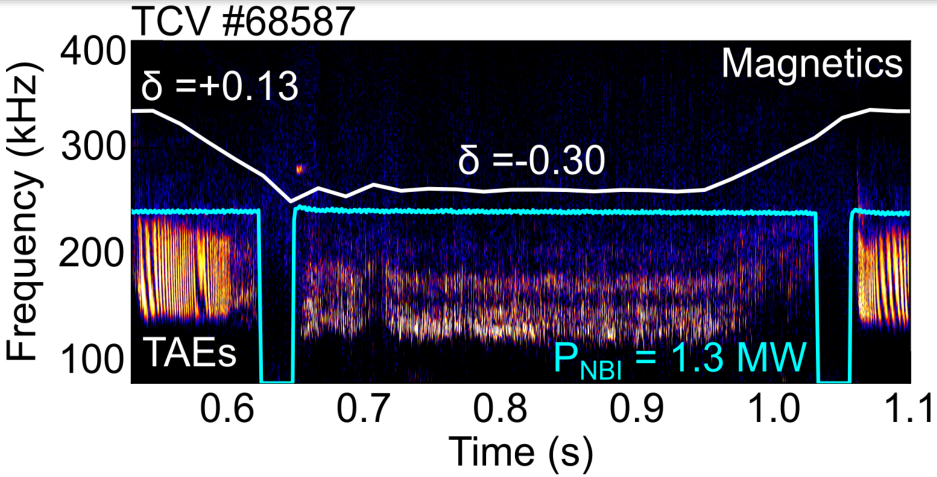


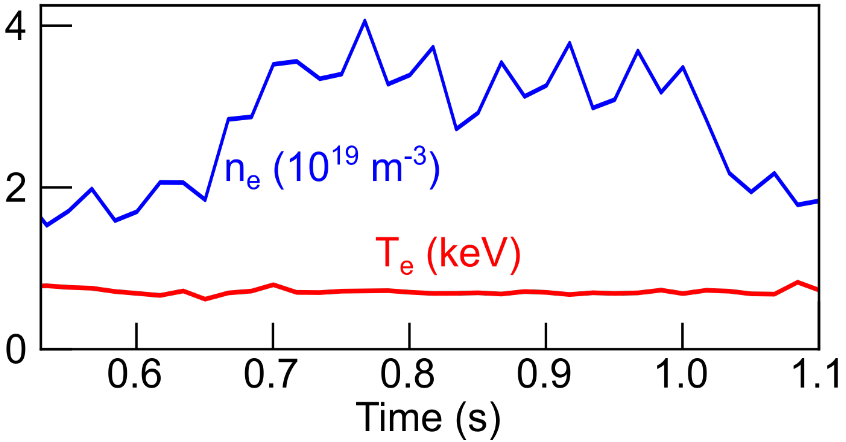
Experiments show strong NT impact on AEs

- Triangularity real-time scan modifies AE activity:
  - Clear EP-drive nature
  - Reduced amplitude ~ 50 %

- Plasma shaping also has an impact on the overall plasma quantities:
  - *q*-profile
  - Plasma density and temperature

- To isolate the effect of the triangularity on the AEs we rely on self-consistent kinetic-MHD simulations





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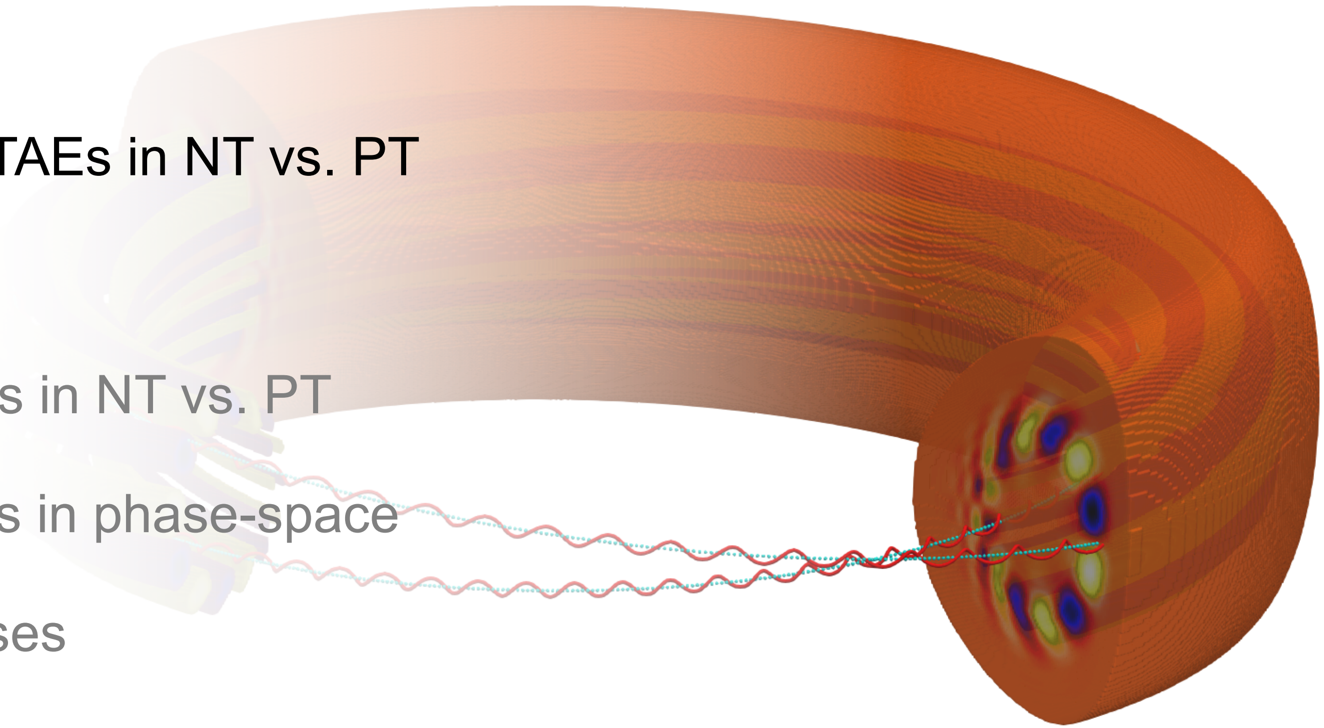


MEGA[9]: Nonlinear 3D hybrid kinetic-MHD code

Bulk plasma

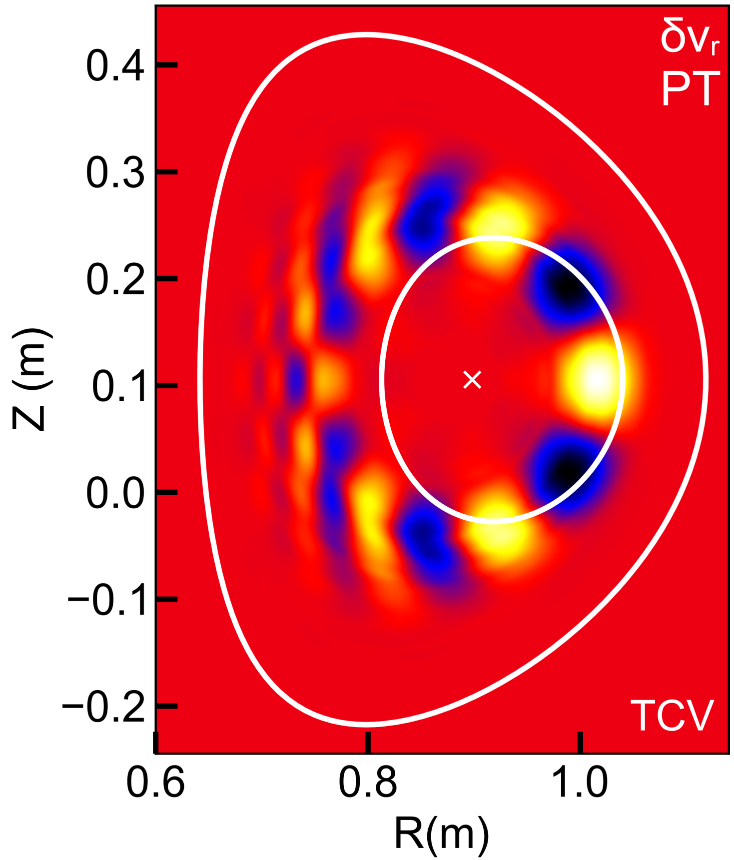
- Resistive full MHD model

Coupling through current density

Fast-ions

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

$$\frac{\partial \vec{U}}{\partial t} + \vec{\nabla} \cdot \left(\vec{v}\vec{U}\right) = -\vec{\nabla} p + \left(\vec{J} - \vec{J}'_{FI}\right) \times \vec{B} + \frac{4}{3}\left(\nu\rho\vec{\nabla}\cdot\vec{v}\right) - \vec{\nabla}\times\left(\nu\rho\vec{\omega}\right)$$

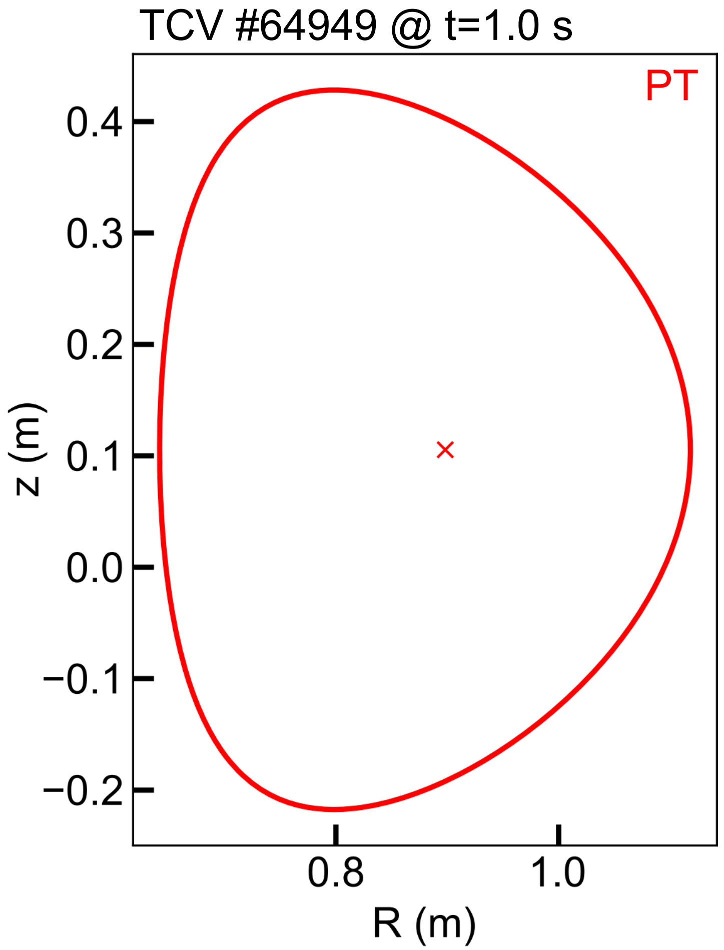


[9] Y. Todo *et al.*, PoP **5** 1321 (1998)

Simulation setup

- L-mode discharge
  - B_t=+1.3T at the axis
  - Co-going I_p=+130 kA

- Co-going NBI heating @ 25 keV as fast-ion source



Simulation setup

- L-mode discharge
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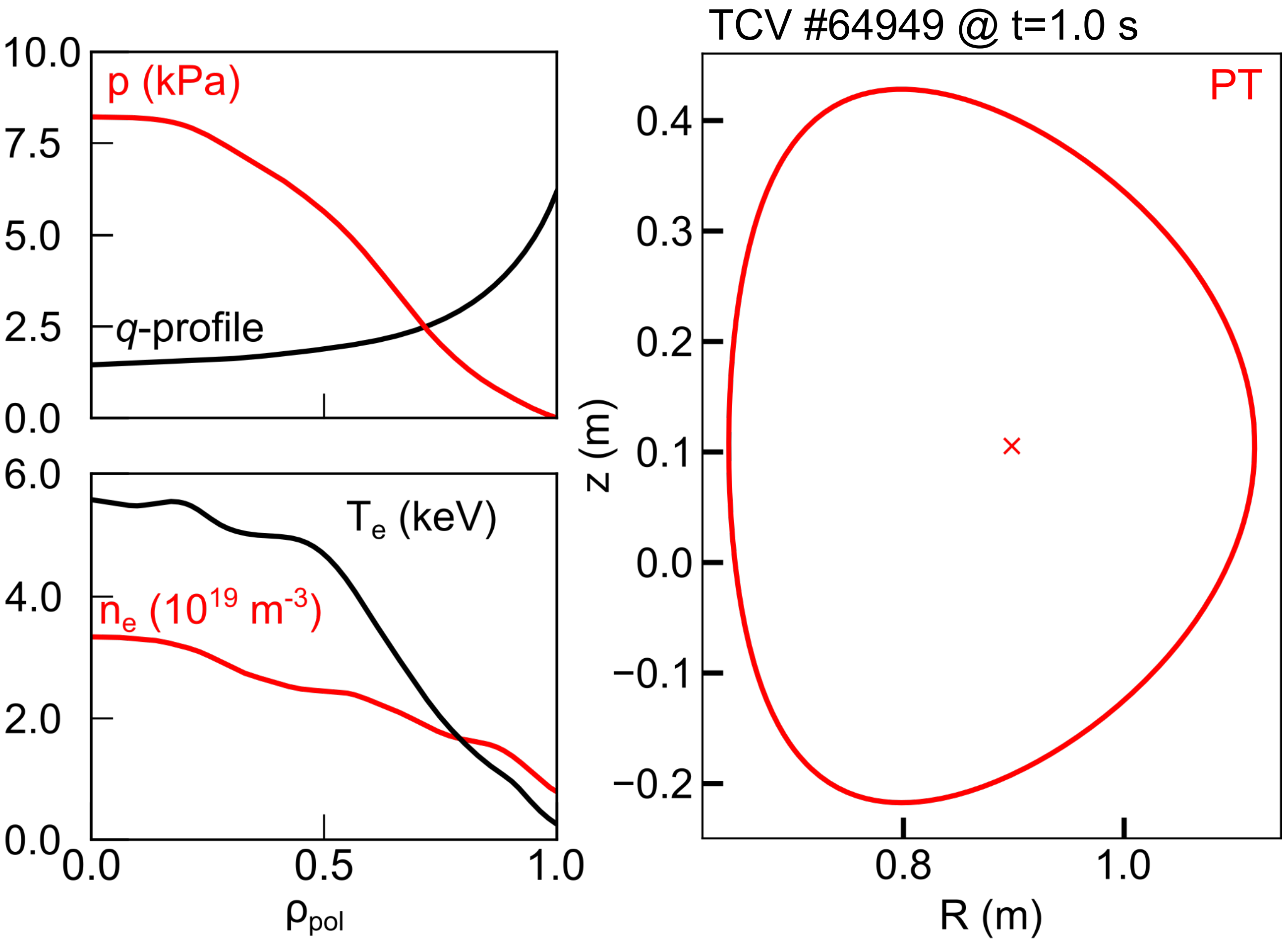
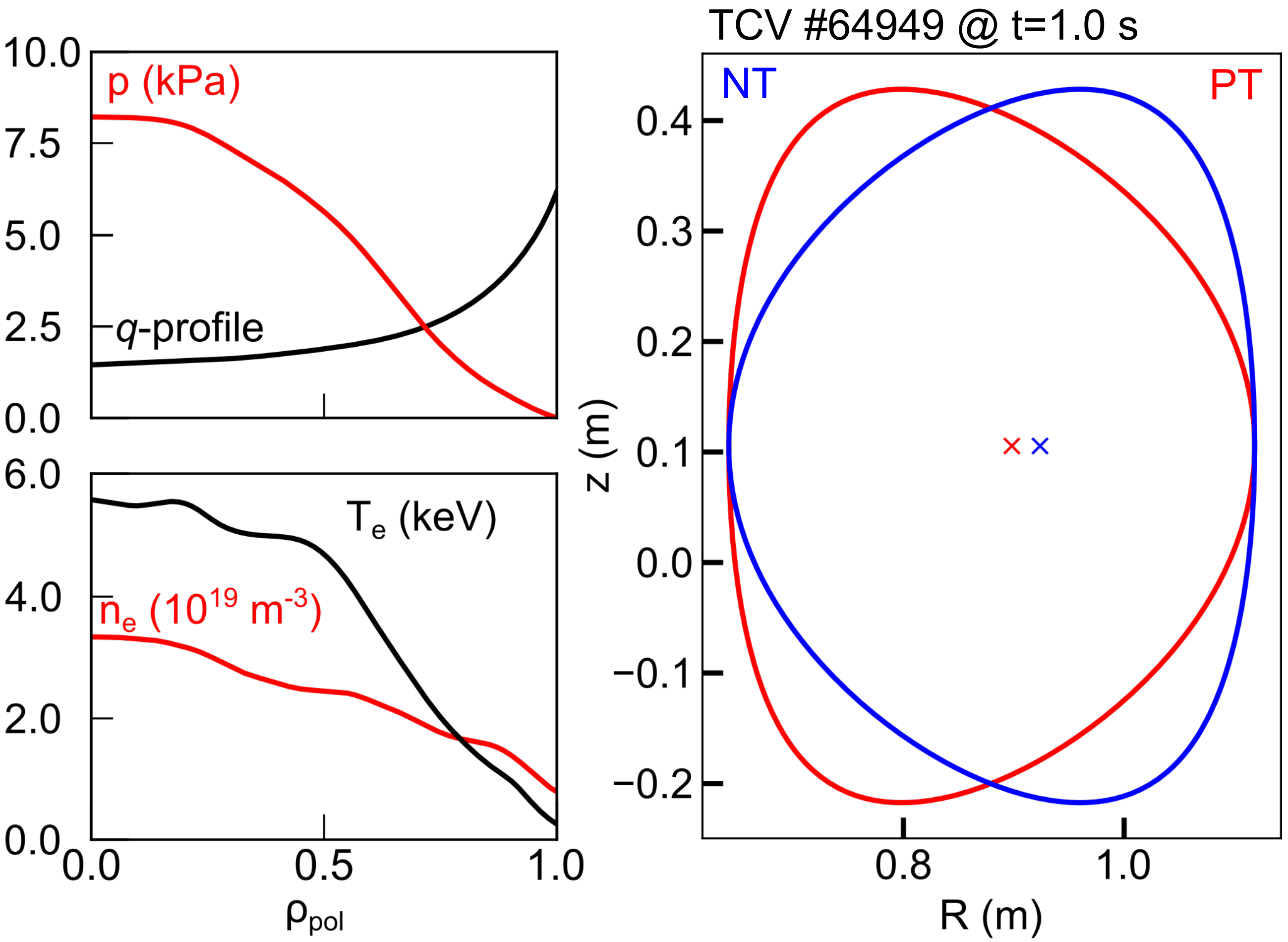
- Kinetic profiles from measurements



Simulation setup

- L-mode discharge
  - B_t=+1.3T at the axis
  - Co-going I_p=+130 kA
- Co-going NBI heating @ 25 keV as fast-ion source
- Kinetic profiles from measurements
- Mirrored PT → NT
- Multi-*n* simulation

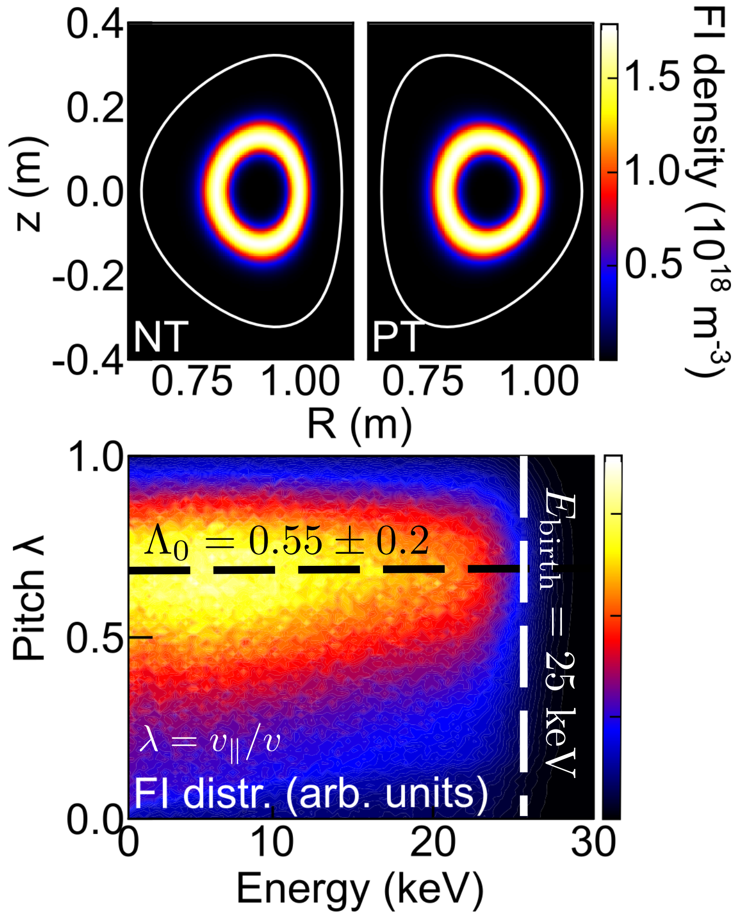


Ad-hoc realistic initial fast-ion distribution

Analytical anisotropic slowing-down distribution

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

Pitch angle $\Lambda_0 \equiv \frac{\mu B_{\mathrm{axis}}}{E}$



Parameter scans to isolate the impact of the δ:

- Injection pitch angle, Λ_0
- Radial profile, ρ_0

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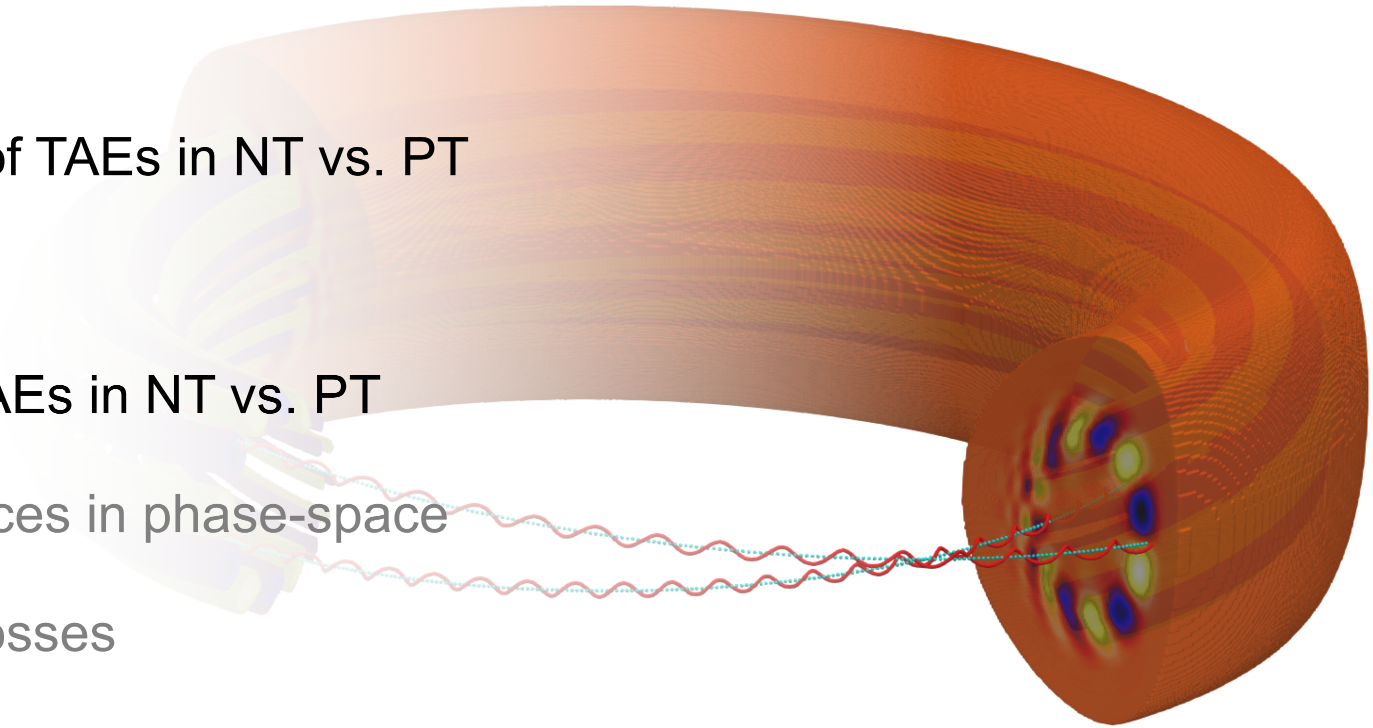
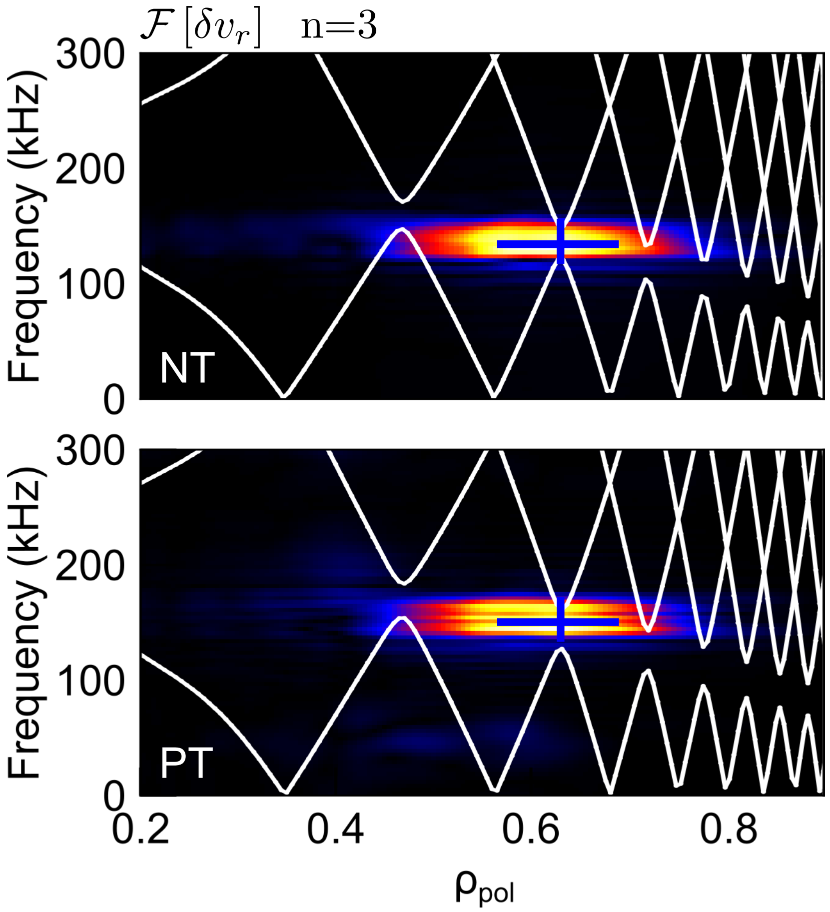


Similar TAE in NT vs. PT develops in simulations

Plasma shaping impacts on the observed TAE activity

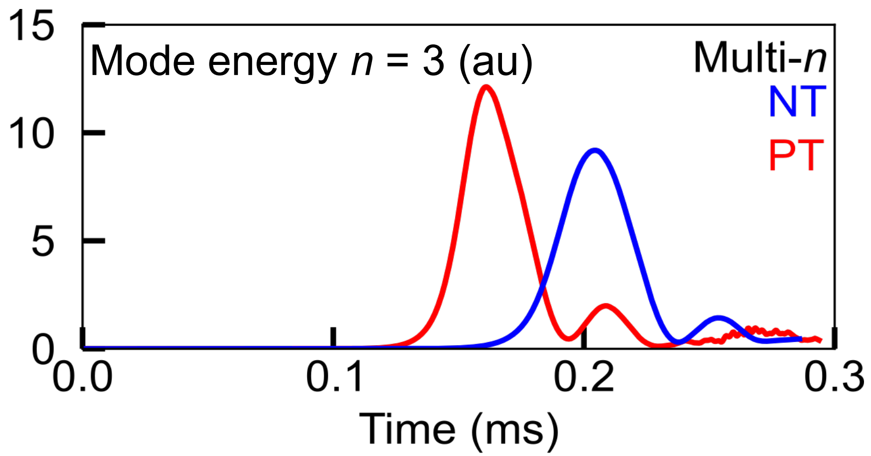
- Shear Alfvén Wave continuum is similar in PT & NT
  - Shafranov shift has negligible impact on the continuum
  - Similar frequency and radial location of the mode in the plasma



TAE is mitigated in NT vs PT

Plasma shaping impacts on the observed TAE activity

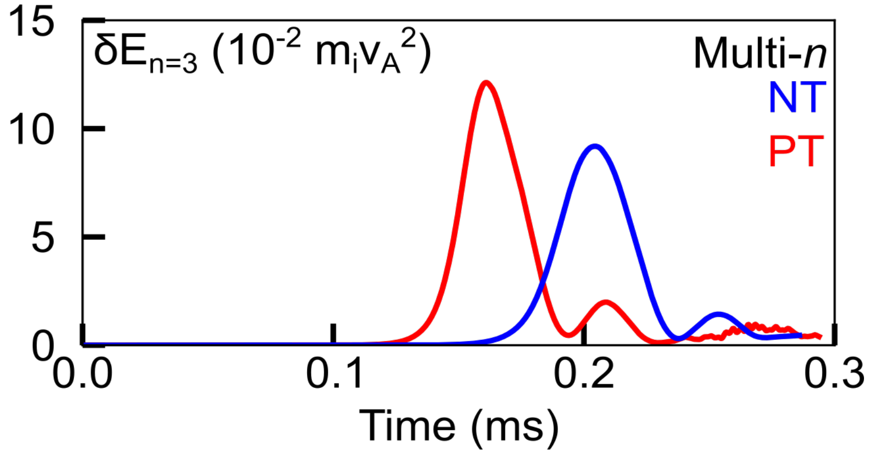
- SAW is similar in PT & NT
- In PT, TAE reaches a ~40% larger energy, compared to NT
- Growth rate is 20% smaller in NT

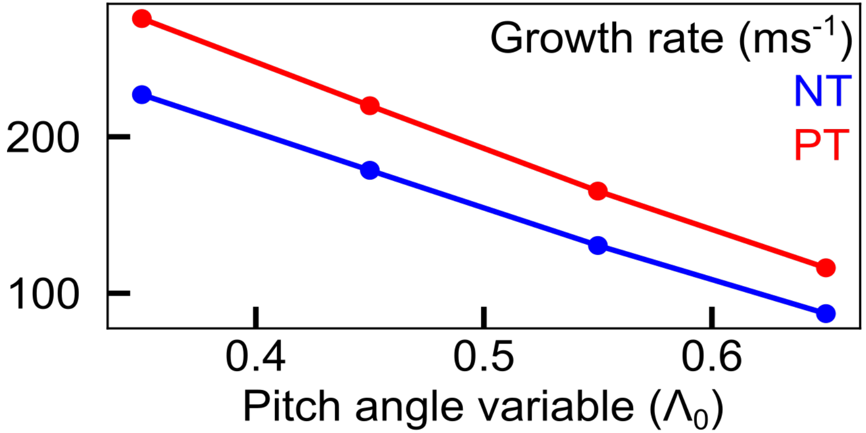


Systematical reduction of the growth rate in NT

Plasma shaping impacts on the observed TAE activity

- SAW is similar in PT & NT
- In PT, TAE reaches a ~40% larger energy, compared to NT
- Growth rate is 20% smaller in NT
- Robust observation independent on the initial fast-ion distribution function:
  - Pitch angle, Λ_0
  - Fast-ion drive location, ρ_0





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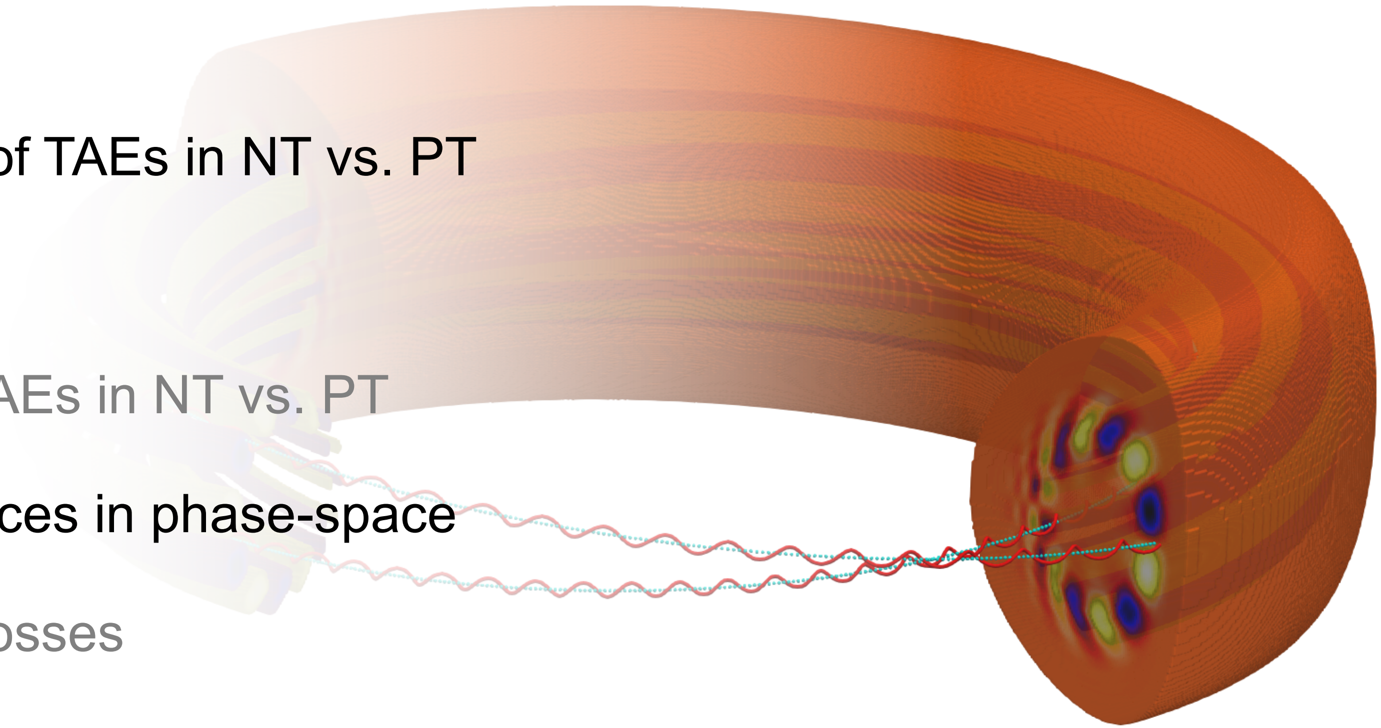

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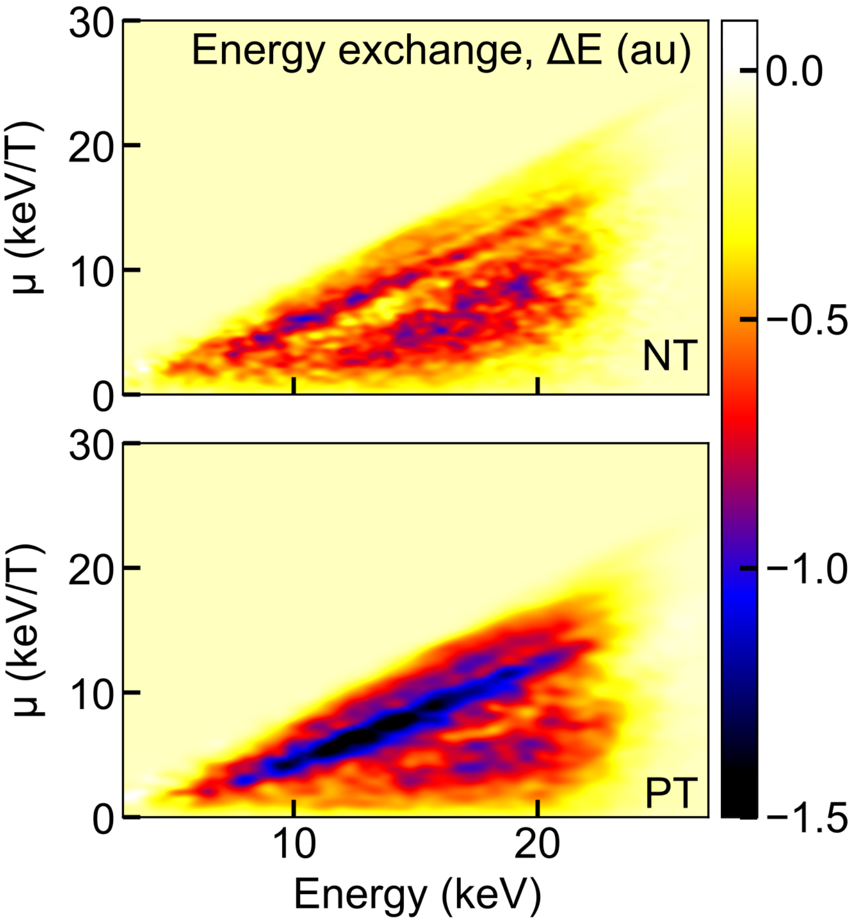
Analysis of the power exchange in the fast-ion phase-space reveals resonant interaction

- Power exchange studied in the constant of motion space of the fast-ions (E, μ), integrated over P_ϕ

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

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

- Two main phase-space volumes providing energy to TAE



Analysis of the power exchange in the fast-ion phase-space reveals resonant interaction

PSFT Plasma Science and Fusion Technology EPFL

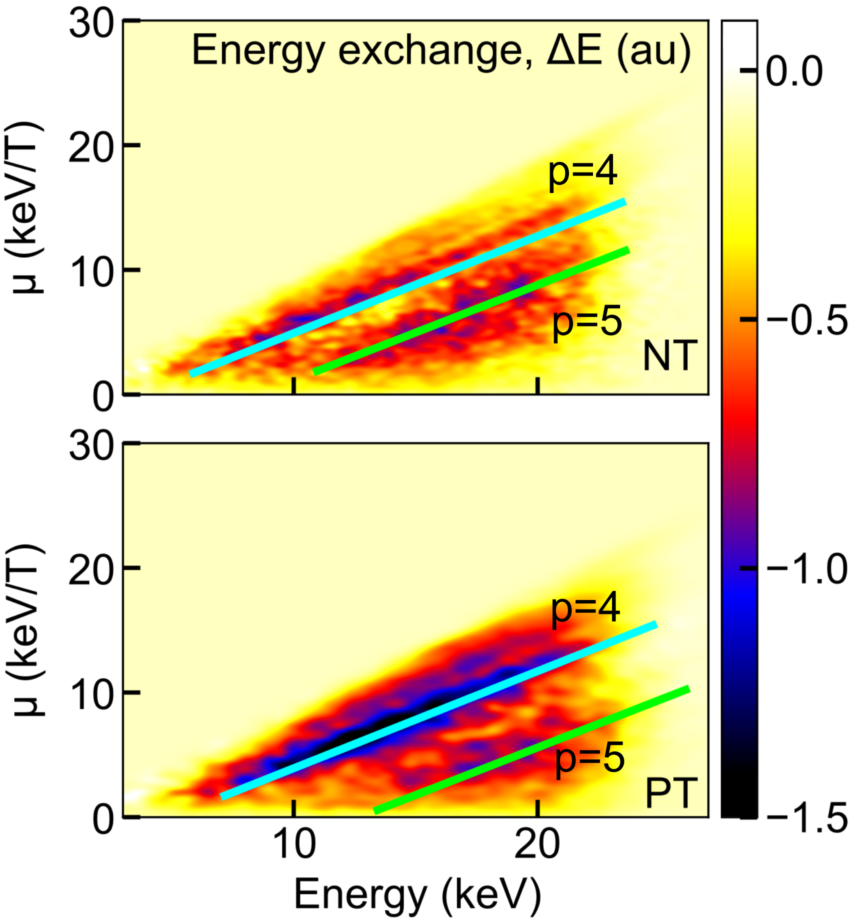
- Power exchange studied in the constant of motion space of the fast-ions (E, μ), integrated over P_ϕ

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

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

- Two main phase-space volumes providing energy to TAE:
  - Fast-ion analytical resonances[10]

$$\omega_{\mathrm{TAE}} = n\bar{\omega}_d + p\omega_\theta$$



[10] F. Zonca *et al*. New. J. Phys. **17** (2015)

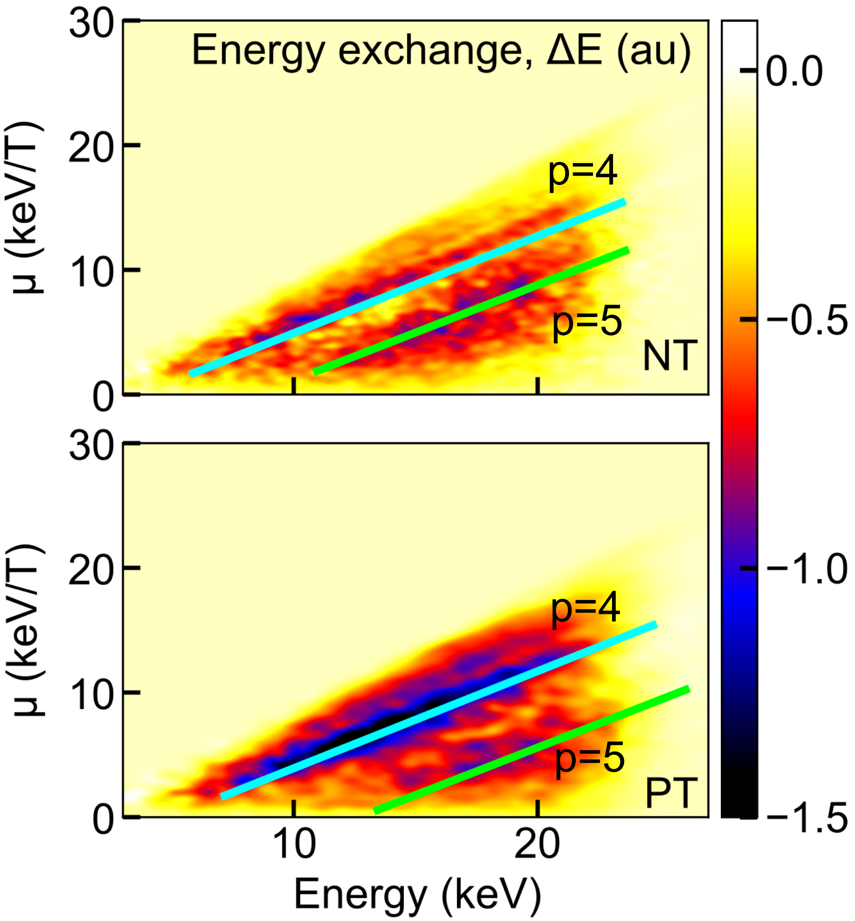
NT damps the lowest sideband harmonic

- Alignment of analytical resonances with structures in fast-ion phase-space.

$$\omega_{\text{TAE}} = n\bar{\omega}_d + p\omega_\theta$$

- In PT, lower sideband harmonic (*p*=4) is most excited.

- In NT, damps lower sideband harmonic (*p*=4).



NT damps the lowest sideband harmonic.

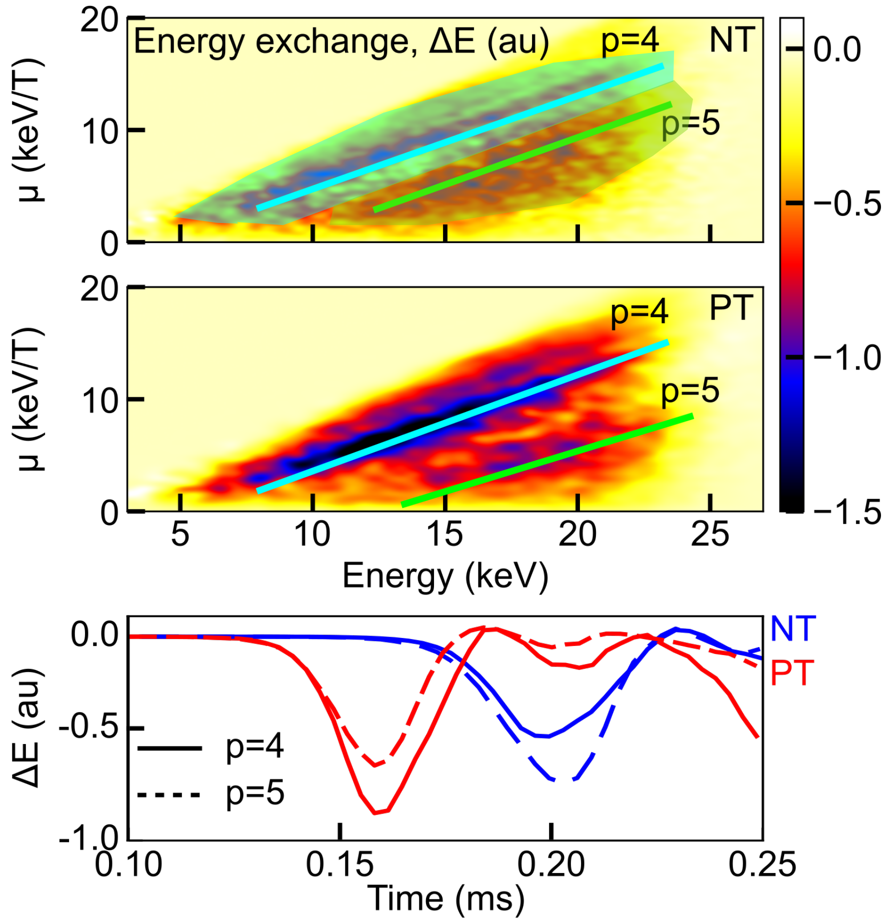
- Alignment of analytical resonances with structures in fast-ion phase-space.

$$\omega_{\mathrm{TAE}} = n\bar{\omega}_d + \left(\textcolor{red}{p} + (m - nq)\right)\omega_{\mathrm{t}}$$

- In PT, lower sideband harmonic (*p*=4) is most excited.

- In NT, damps lower sideband harmonic (*p*=4).

- Behavior reproduced at all time points.



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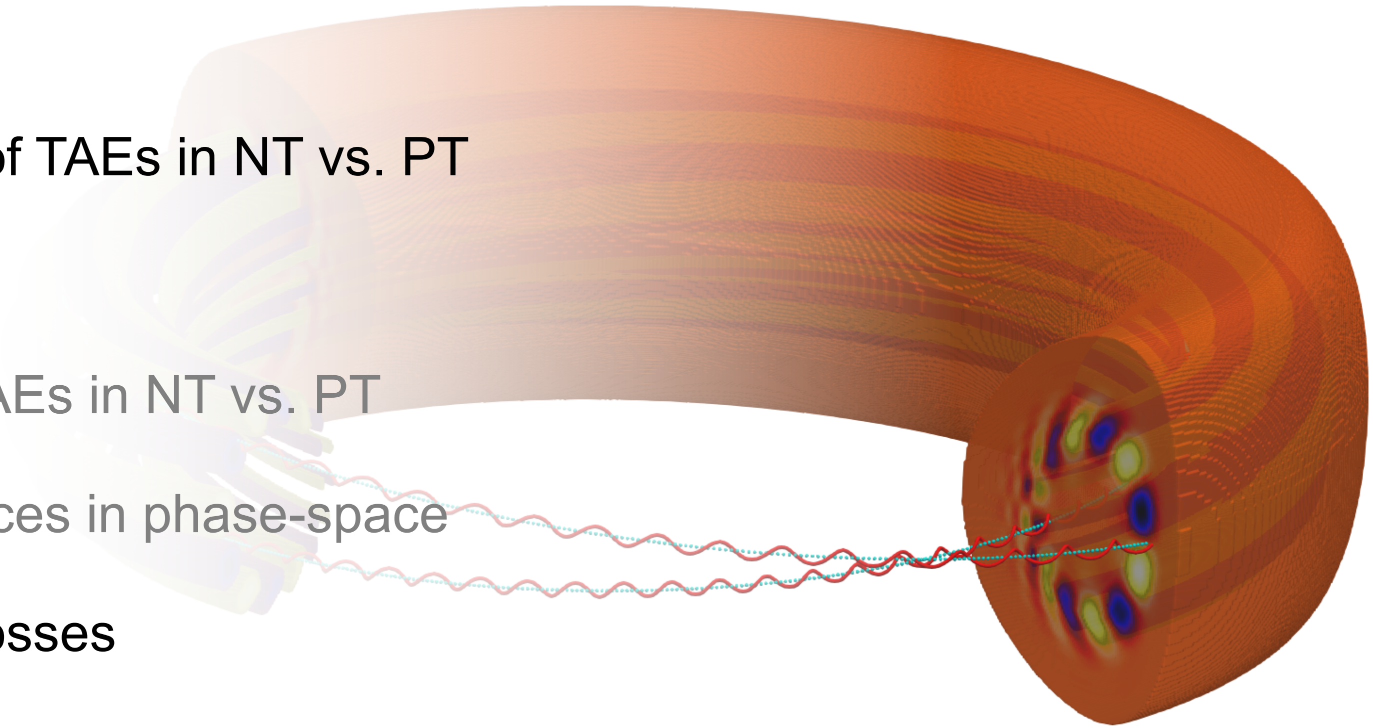
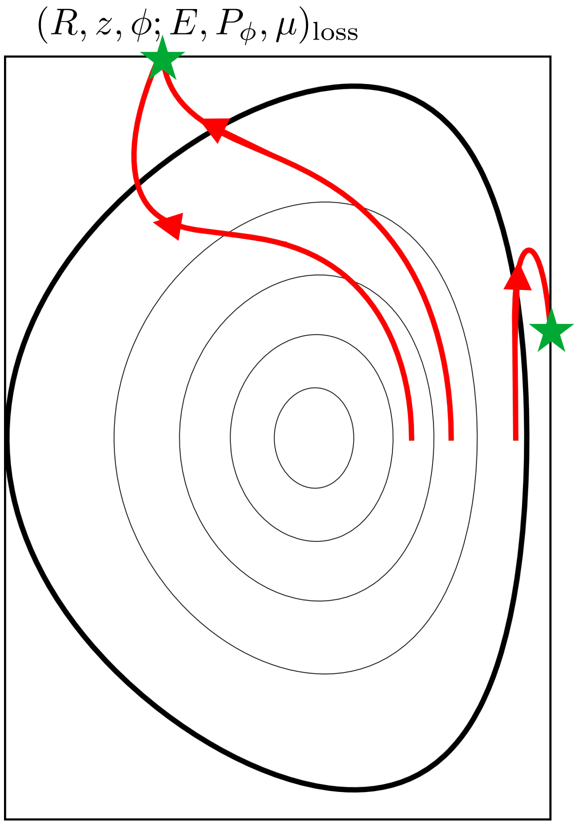


A synthetic fast-ion loss detector

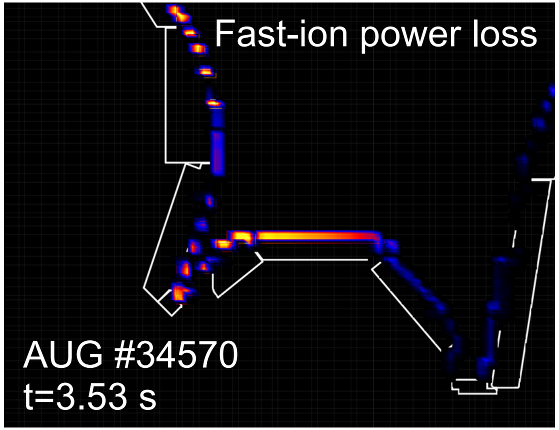
- TAEs are known to produce significant fast-ion transport and losses
- Self-consistent losses can be evaluated with a synthetic wall implemented in MEGA[12]

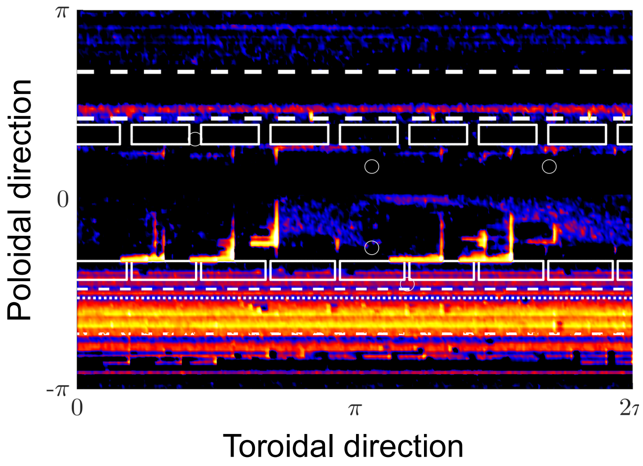


[12]P. Oyola *et al.*, RSI **92** (2021)

3D wall and 2D implemented in MEGA and tested

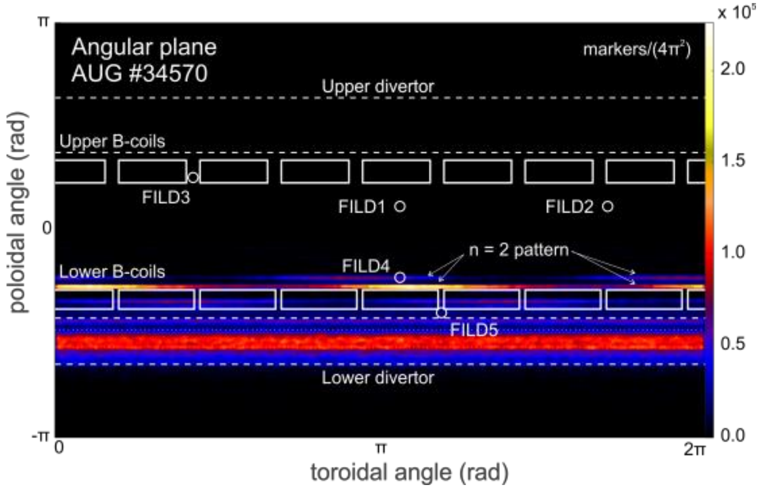
- TAEs are known to produce significant fast-ion transport and losses
- Self-consistent losses can be evaluated with a synthetic wall implemented in MEGA
- Geometrical heat loads from the fast-ion transport can be detected
  - Prompt losses





Wall losses show correspondence with RMPs

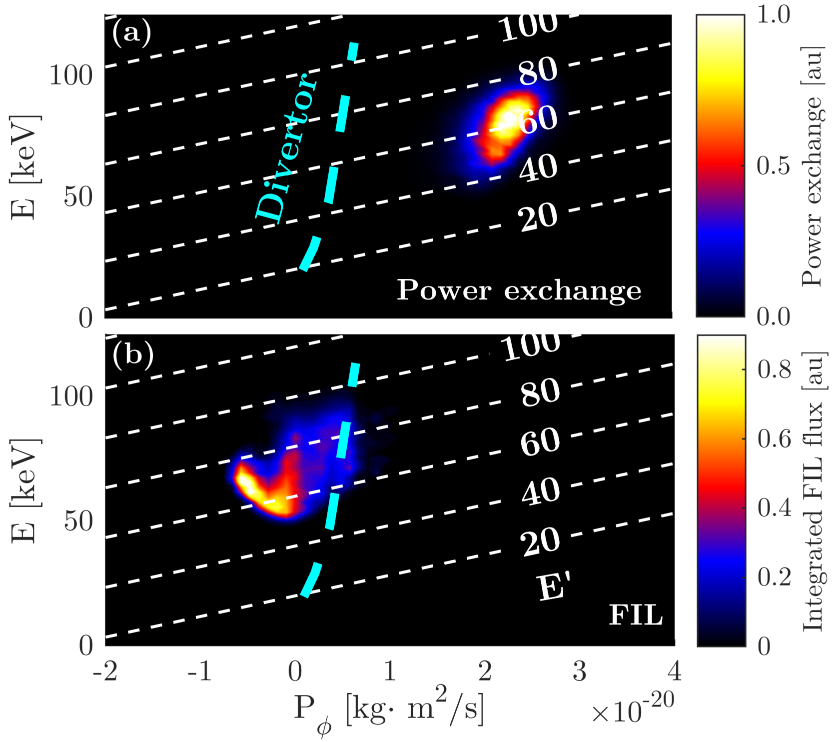
- TAEs are known to produce significant fast-ion transport and losses
- Self-consistent losses can be evaluated with a synthetic wall implemented in MEGA
- Geometrical heat loads from the fast-ion transport can be detected
  - Prompt losses
  - Reproduces the MP-induced transport



J. Gonzalez-Martin *et al*, 45th EPS Conference (2018)

Wall losses show correspondence with RMPs

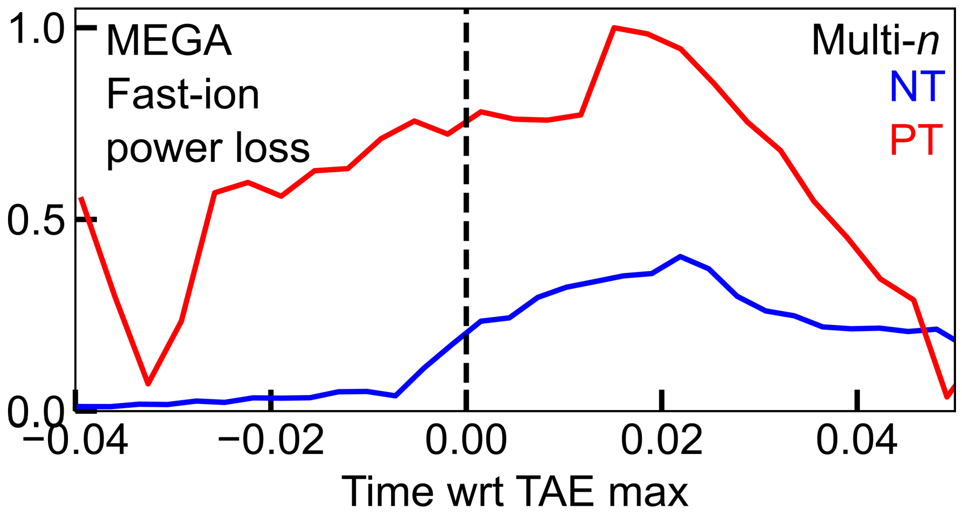
- TAEs are known to produce significant fast-ion transport and losses
- Self-consistent losses can be evaluated with a synthetic wall implemented in MEGA
- Geometrical heat loads from the fast-ion transport can be detected
  - Prompt losses
  - Reproduces the MP-induced transport
  - Reproduces important physical features



P. Oyola *et al.*, RSI **92** (2021)

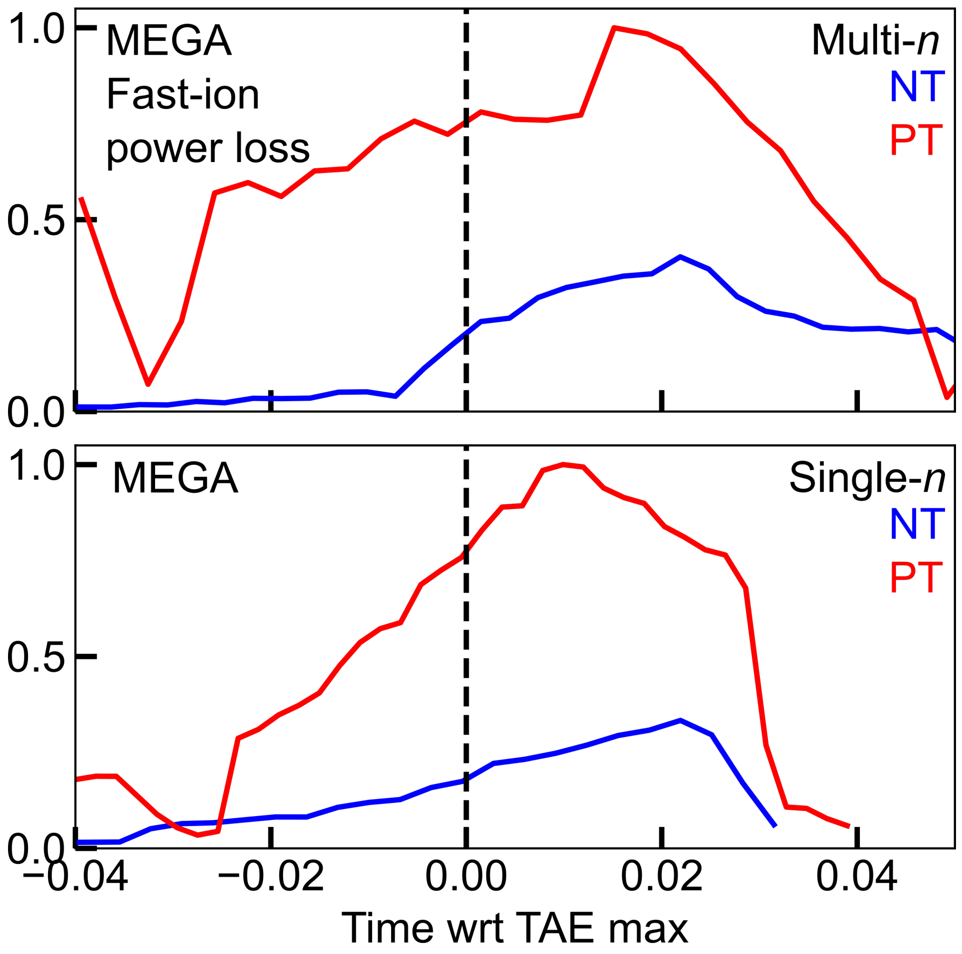
TAE-induced fast-ion losses are 3x lower in NT

- 2D wall implemented in MEGA for TCV tokamak
- Correlated fast-ion losses bursts with TAE saturation
- Fast-ion power loss reduced **3x** in NT compared to PT



Single-*n* MEGA simulation reproduces the losses and TAE characteristics

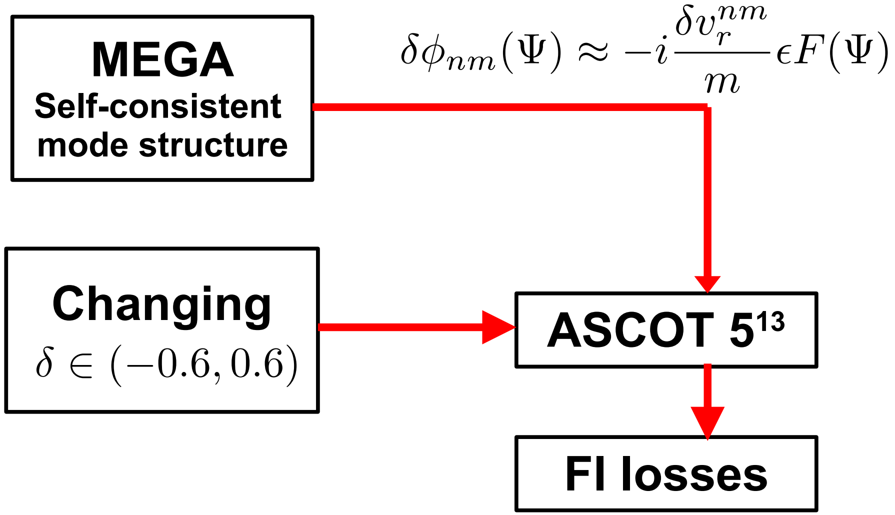
- Single-*n* simulation reproduces qualitatively reproduces the fast-ion transport:
  - Correlated losses
  - Enhanced confinement for NT case

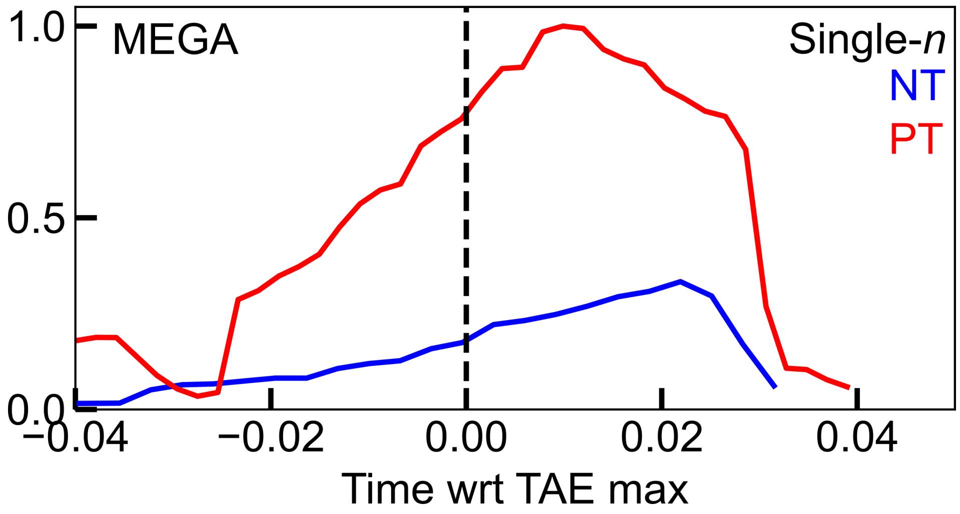


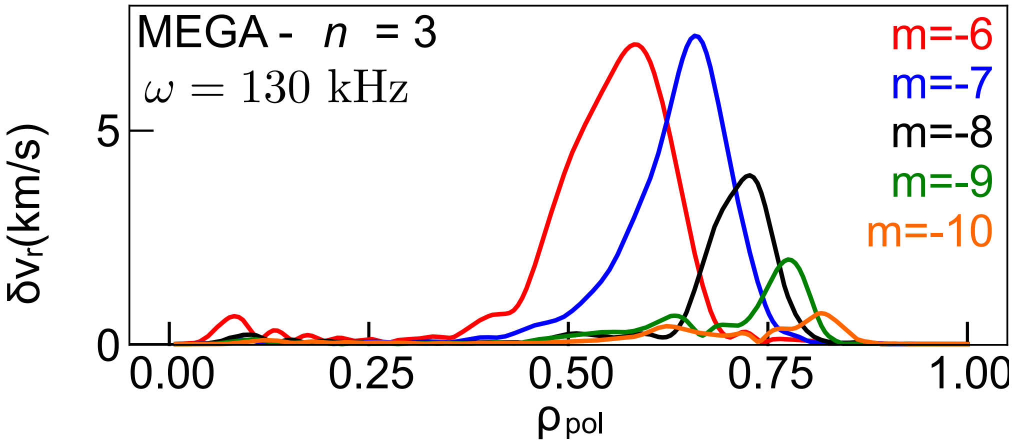
ASCOT5 simulates TAE-induced fast-ion losses

- Single-*n* simulation reproduces qualitatively reproduces the fast-ion transport

- Extending it to more triangularities



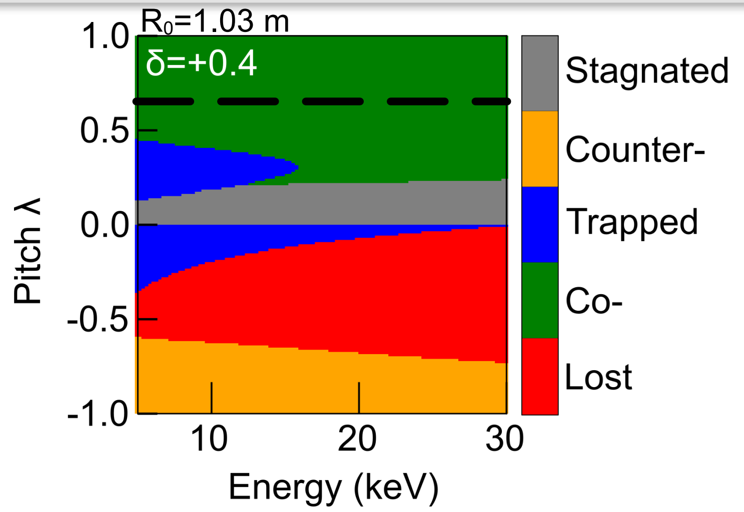




[13] E. Hirvijoki *et al.*, Comput. Phys. Comm. **185** (2014)

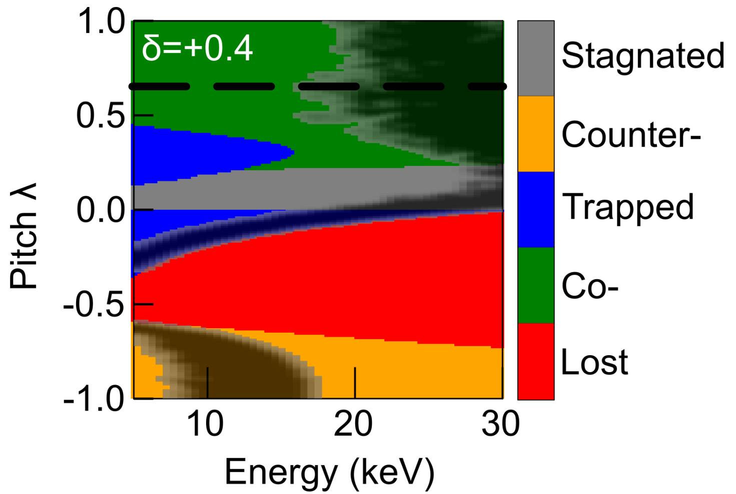
AE-induced losses are localized in co-going

- Single-*n* simulation reproduces qualitatively reproduces the fast-ion transport
- Extending it to more triangularities
  - Co-injected particles are resonantly transported.
  - Losses in stagnated, trapped and counter are expected.



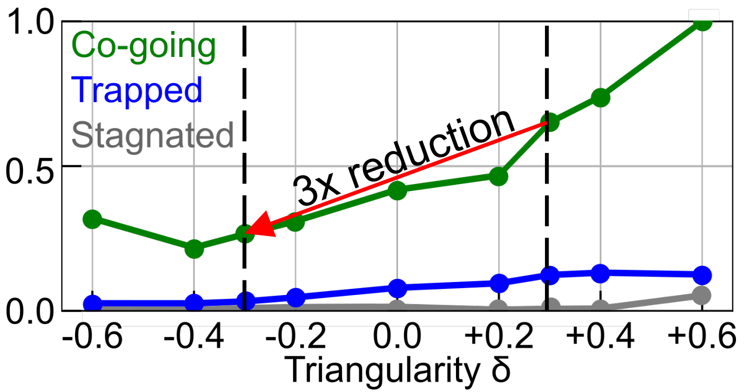
AE-induced losses decrease for deeper NT

- Single-*n* simulation reproduces qualitatively reproduces the fast-ion transport



- Extending it to more triangularities

- Resonantly transported losses are consistently reduced as deeper NT are reached!



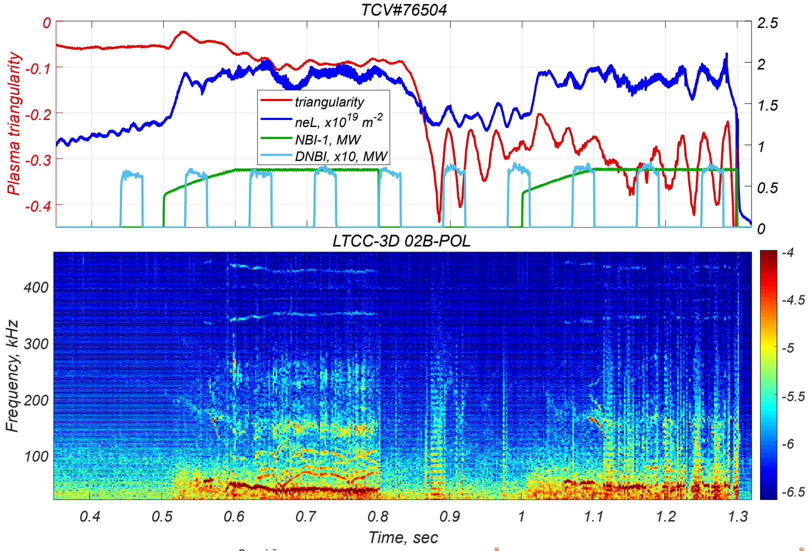
First TCV experiments with FILD measurements points to confirm the results

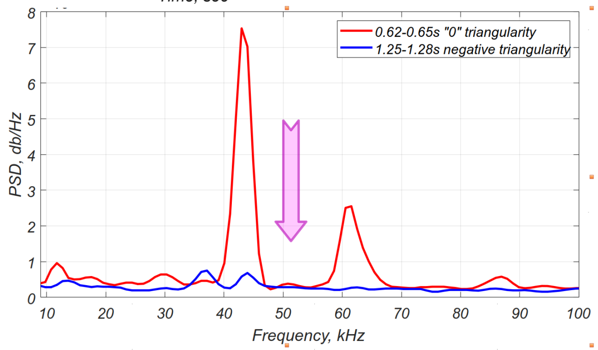
- Single-*n* simulation reproduces qualitatively reproduces the fast-ion transport:

- Extending it to more triangularities

- Resonantly transported losses are consistently reduced as deeper NT are reached!

- First empirical hints proving mitigated AE-induced losses at TCV

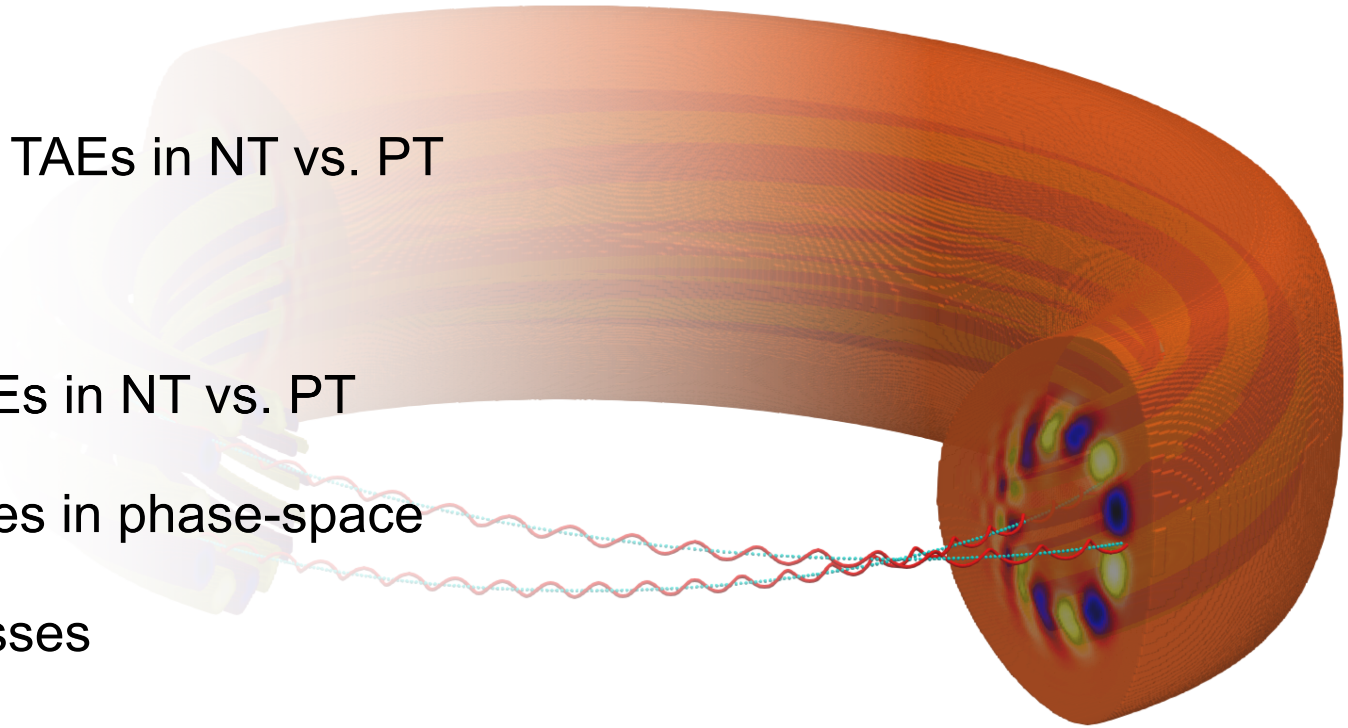




Courtesy of A. N. Karpushov and J. Poley-Sanjuan, EPFL

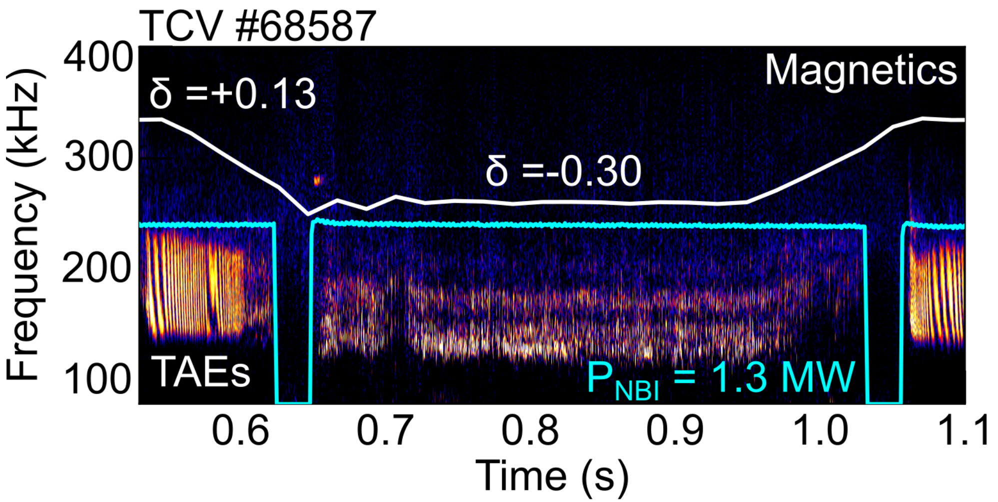
Outline

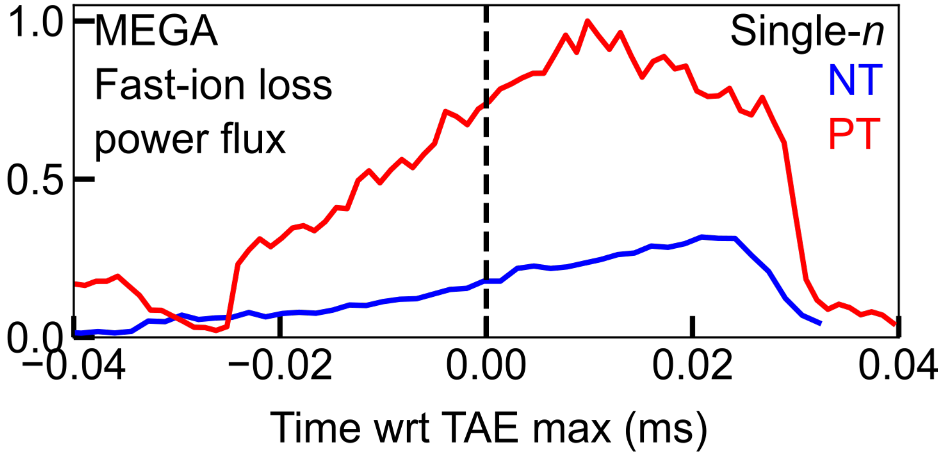
- NT experiments at TCV
- Hybrid kinetic modeling of TAEs in NT vs. PT
  - MEGA
  - Overall behaviour of TAEs in NT vs. PT
  - Wave-particle resonances in phase-space
  - TAE-induced fast-ion losses
- Conclusions



Conclusions

- TAEs appear weaker in NT than in its counterpart PT.
- MEGA sims used to isolate the δ effects.
- ~40% lower energy in NT with respect to PT.
- Lower transit harmonics are damped in NT.
- Fast-ion losses are 3x lower in NT.





Backup slides

This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

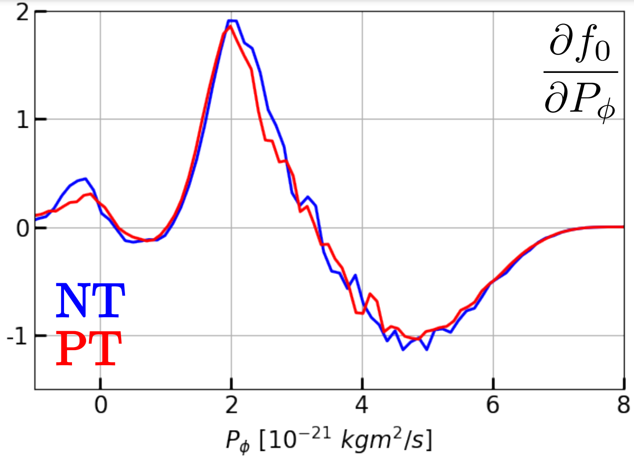
Initial FI drive is the same for NT and PT

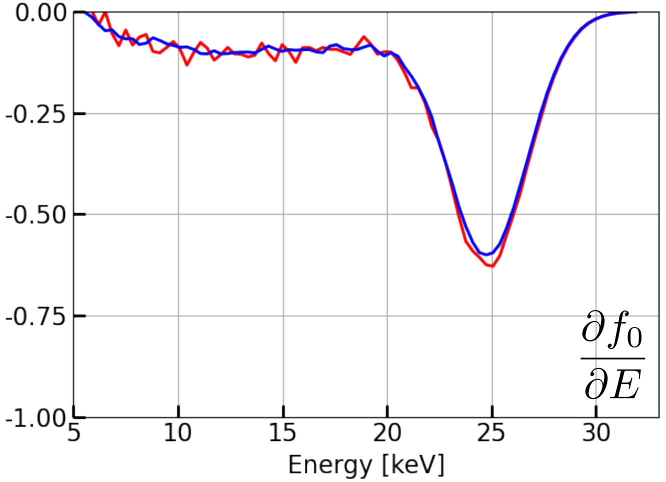
Analytical slowing-down distribution:

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

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

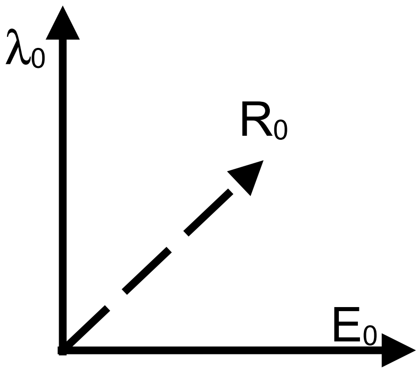
$$\gamma_{\mathrm{TAE}} \propto \beta_{\mathrm{FI}} \left(\frac{\partial f_0}{\partial E} + \frac{n}{\omega}\frac{\partial f_0}{\partial P_\phi}\right)$$

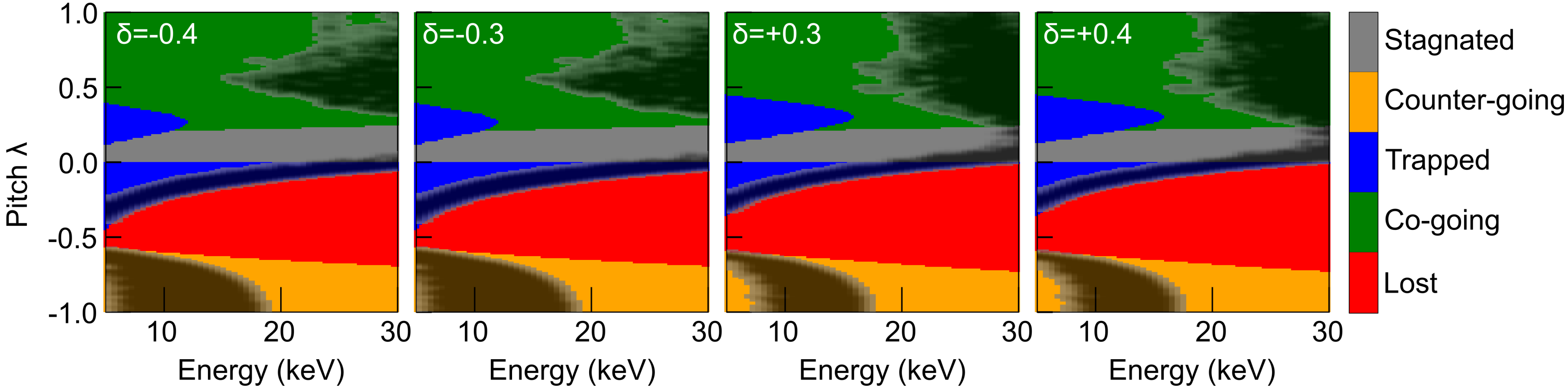




Phase-space topology

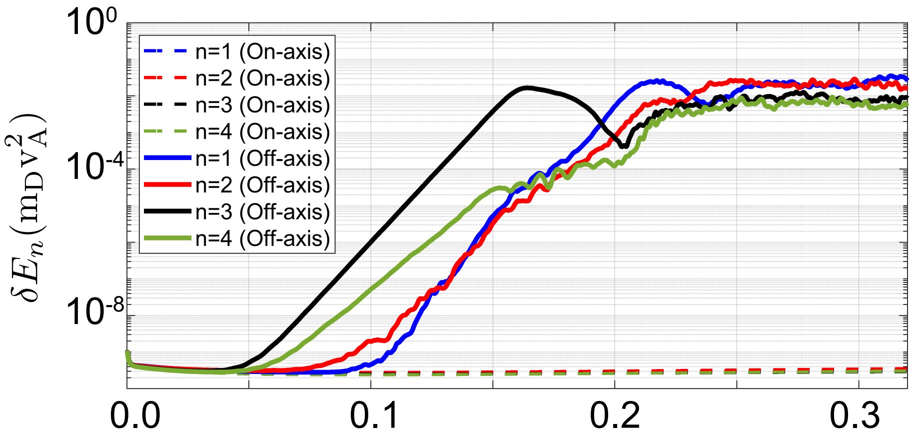
- The phase-space is similar for all δ
  - Slightly more broader trapped region for increasing $+\delta$.
- Counter-going particles ($\lambda < 0$) are badly confined:
  - Close to the loss-boundary along the R_0 direction
  - Small perturbations lead to loss of confinement.
  - Only good confinement at core.

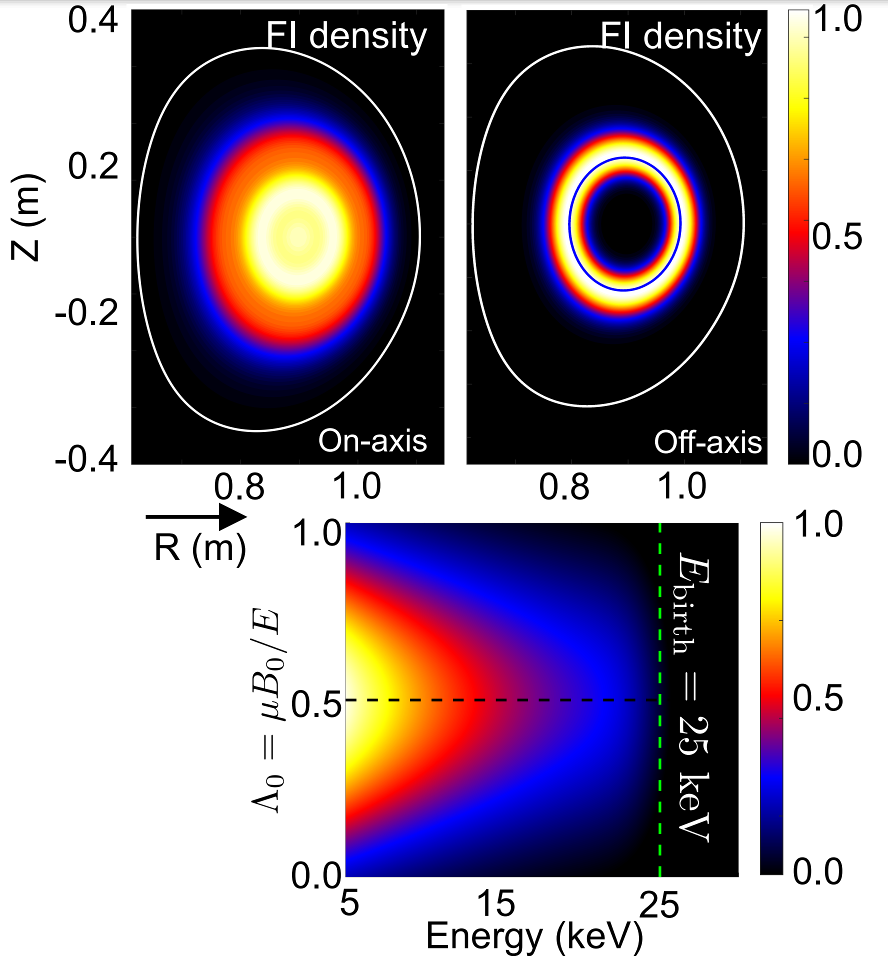




On-axis NBI vs. off-axis NBI

- On-axis FI distribution in MEGA simulations do not reveal any TAE activity.
- TAE activity only with an off-axis distribution



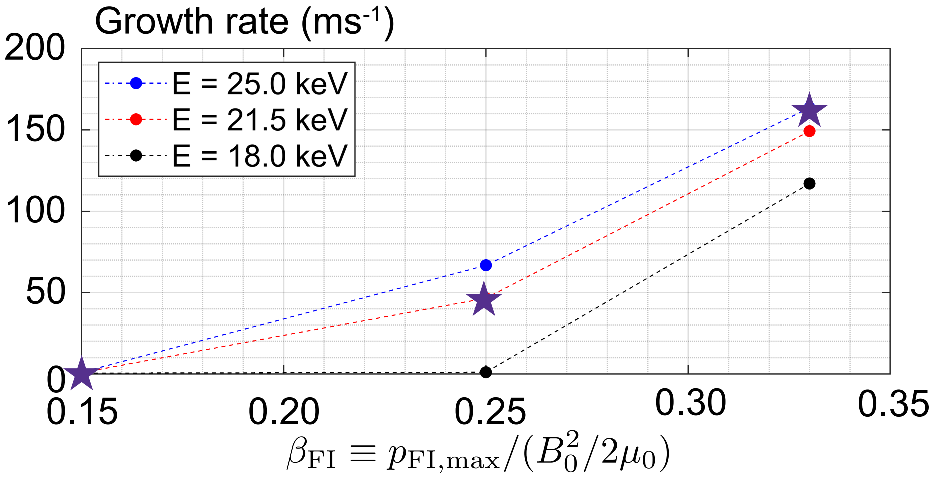


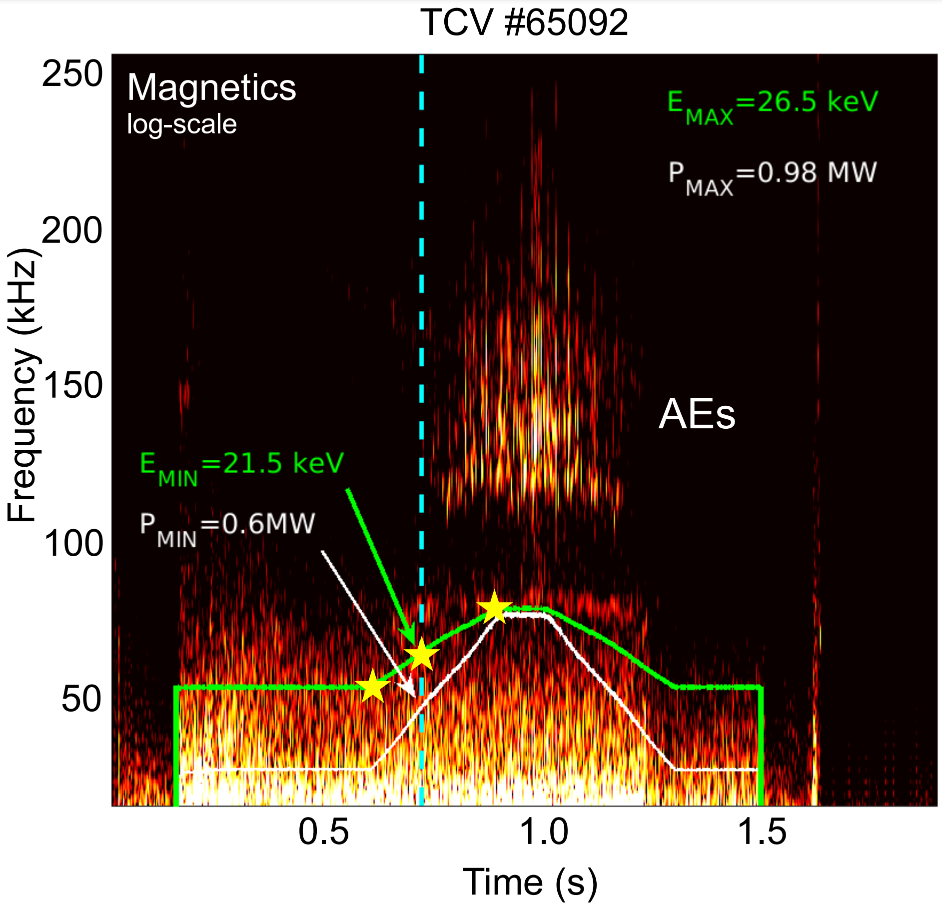
M. García-Muñoz *et al.*, EPS Conference (2021)

MEGA reproduces the experimental energy threshold in experiments

- MEGA reproduces power/energy threshold to trigger TAEs

$$P_{\rm NBI} \gtrsim 0.6\ {\rm MW}$$
$$E_{\rm NBI} \gtrsim 21\ {\rm keV}$$





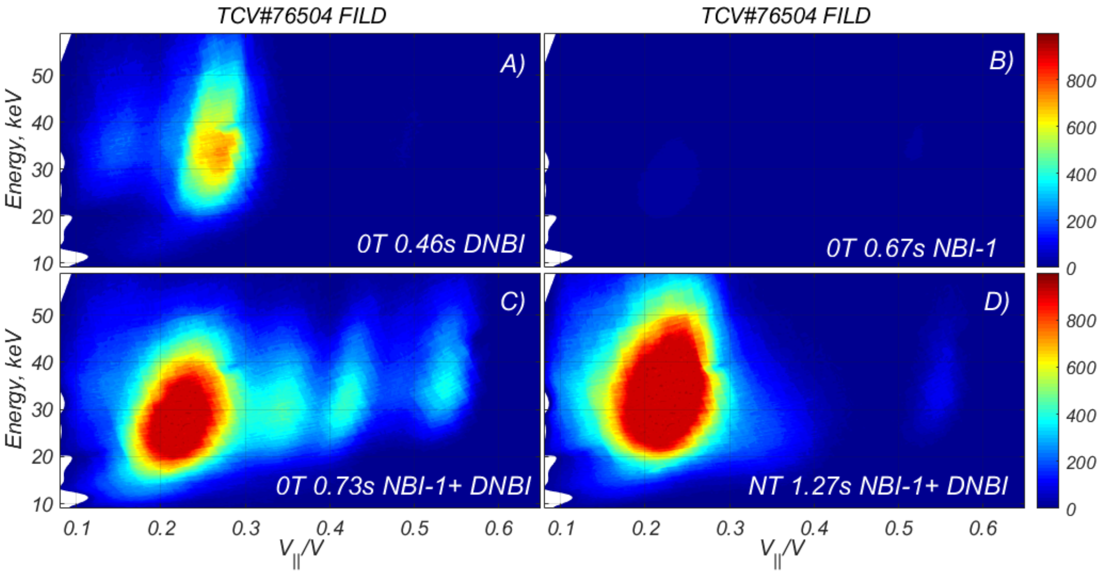
M. García-Muñoz *et al.*, EPS Conference (2021)

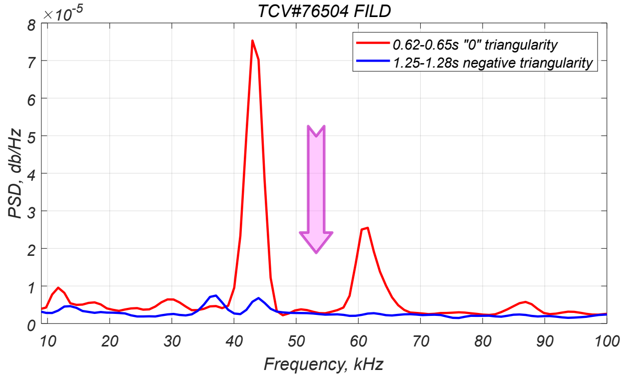
Observed improvement in fast-ion confinement in NT plasmas at TCV

- Fast-ion losses at λ ~ 0.2:
  - 20-50 keV only during the D-NBI
- Fast-ion losses with higher λ:
  - Only with NBI-1 and AE activity

Interpretation:

- NBI-1 (Λ ~ 0.6-1) excites TAEs
- TAEs interact with D-NBI ions at Λ ~0.3
  - DNBI losses detected with FILD



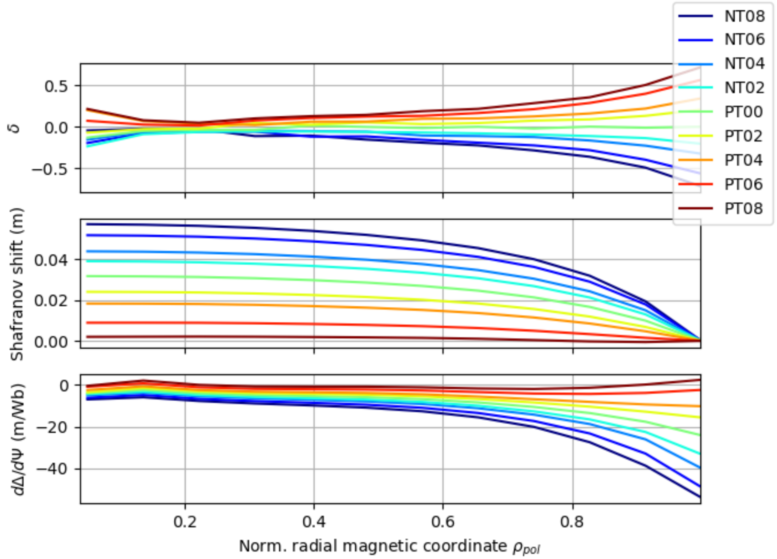


A. N. Karpushov *et al.*, EPS 2023

Larger poloidally varying resonant term

- The poloidally varying contribution in the resonance for deeply passing depends explicitly on the Shafranov shift[12].

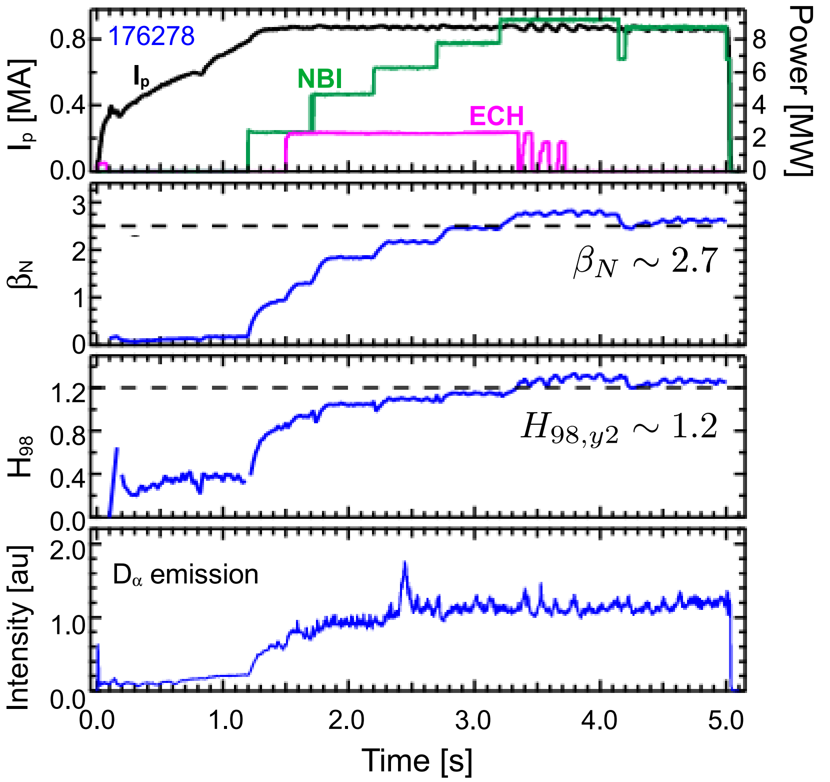
$$\tilde{M} \approx -s \cdot \left(2\cos(\omega) + 2\sum_m \frac{S_m}{r} \cos((m-1)\,\omega) + \Delta' \right)$$



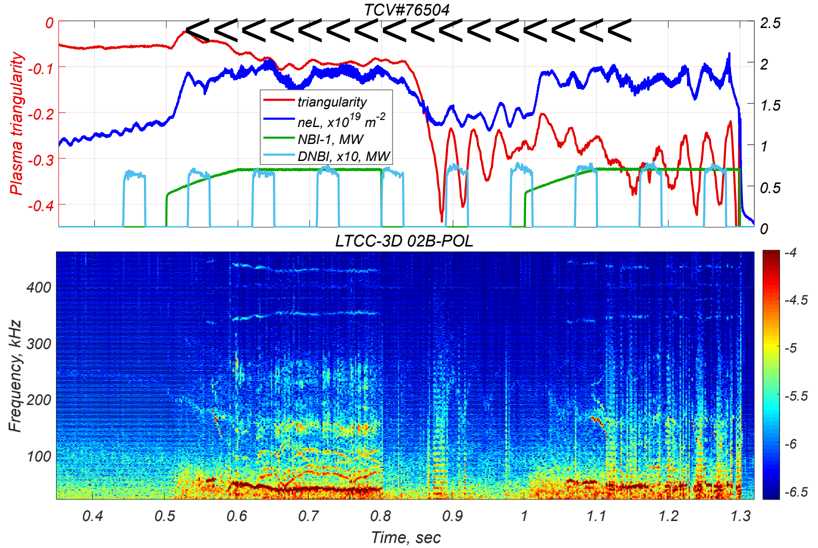
[12]J. P. Graves *et al.*, PPCF **55** (2013)

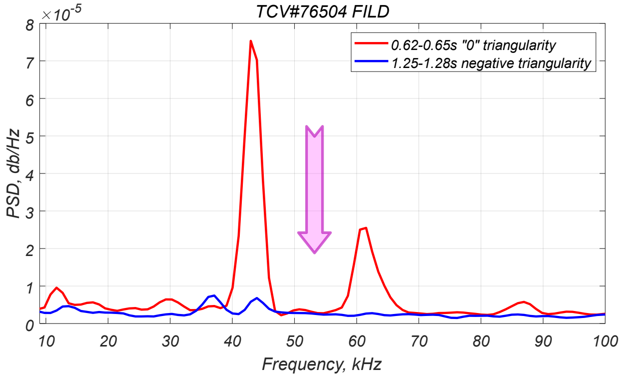
NT is an ELM-free regime with H-mode-like confinement

- Strong reduction of electron heat flux in NT was first observed in TCV[12,13].
  - TEM suppression in -δ [14]
- DIII-D team first showed that confinement is similar to PT in H-mode[15].
  - H-mode-like confinement in NT L-mode.
  - Natural ELM-free scenario.
- Assessment of AEs and fast-ion transport.



[12] J. -M. Moret *et al.*, Phys. Rev. Lett. **79** 2057 (1997)
[13] Y. Camenen *et al.*, Nucl. Fusion **47** 510-516 (2007)
[14] A. Marinoni *et al.*, Plasm. Phys. Controll. Fus. **51** 055016 (2009)
[15] M. E. Austin *et al.*, Phys. Rev. Lett. **122** 115001 (2019)


TCV#76504
Plasma triangularity
triangularity
neL, x10^19 m^-2
NBI-1, MW
DNBI, x10, MW
LTCC-3D 02B-POL
Frequency, kHz
Time, sec


TCV#76504 FILD
×10^-5
0.62-0.65s "0" triangularity
1.25-1.28s negative triangularity
PSD, db/Hz
Frequency, kHz

Magnetic drifts are stronger in NT cases

Using the orbit-resonance analysis[11] framework:

- NT particles feel stronger ∇B-drift
- Increased phase slippage (detuning) in NT compared to PT
- Averages to lower energy transfer