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Study of TAE effects on the global confinement in TCV L-mode plasmas

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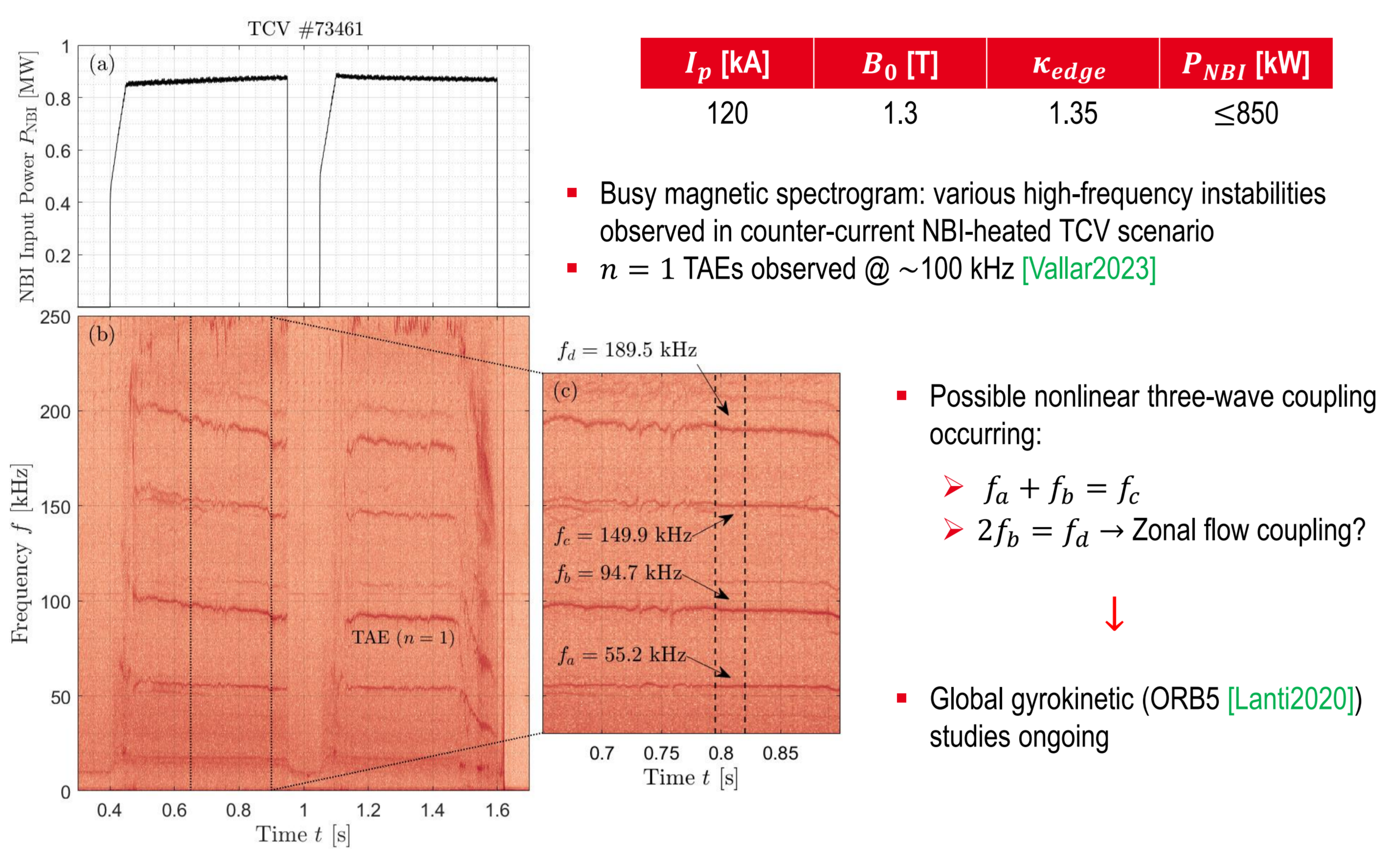
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This work is under review in *Frontiers in Physics* for the Special Issue *Impact of highly energetic ions on magnetically confined plasmas*

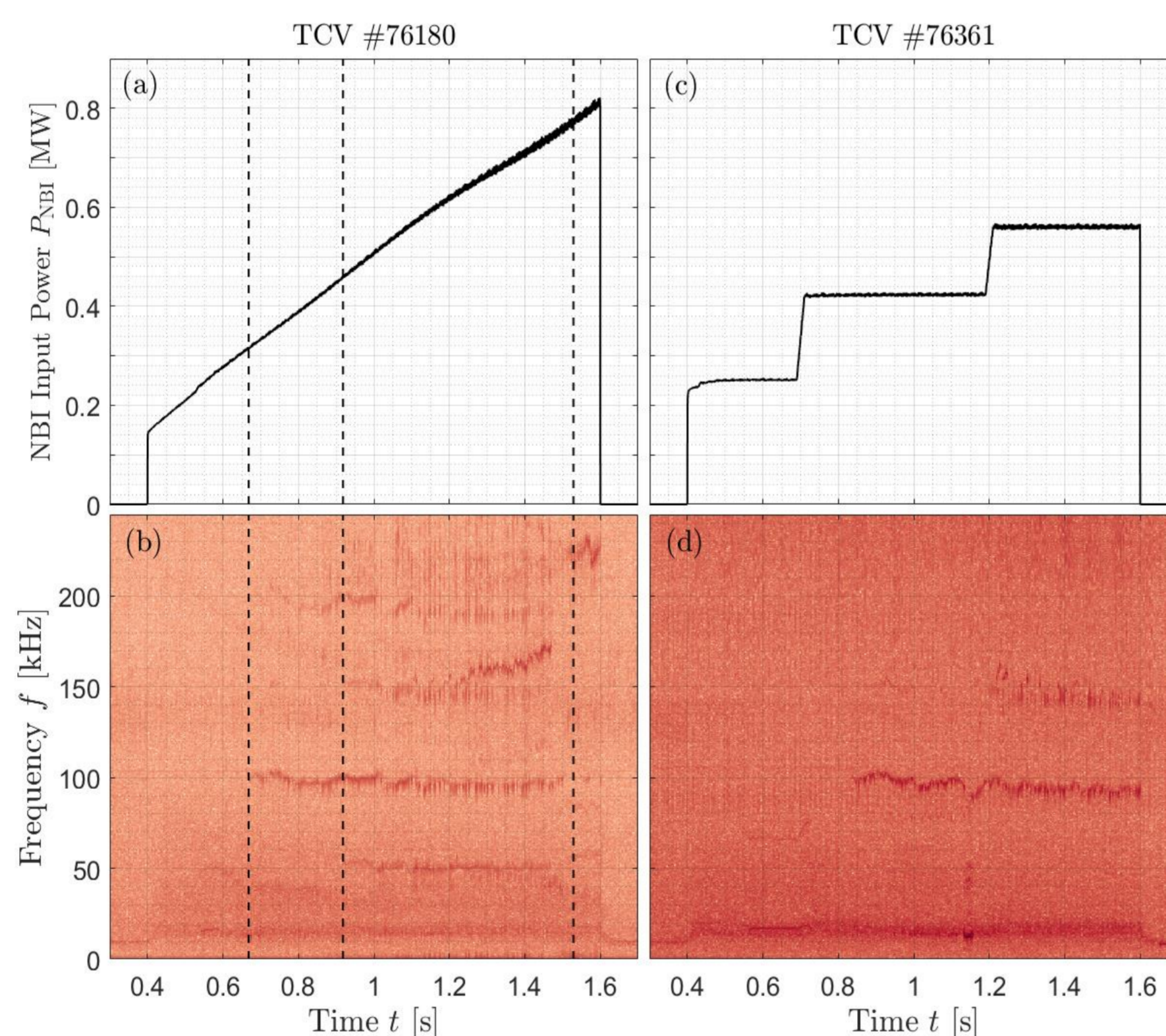
Motivations & Background

- TAEs expected to be destabilized in ITER [Pinches2016] → What the effect on plasma confinement?
 - Stabilization of Ion-Temperature-Gradient (ITG) turbulent transport due to Fast-ion-triggered complex mechanism involving TAEs and enhanced zonal flows [Citrin2013, Garcia2015, DiSiena2019, Garcia2022, Citrin2023]
 - Extended the beneficial mechanism to unstable Toroidal Alfvén Eigenmodes (TAEs) in JET L-mode plasmas with MeV-range fast ions [Mazzi2022]
- Open question:** Is this complex and beneficial mechanism *universal* (devices / turbulent regimes)?
- Observed TAEs destabilized in TCV L-mode plasma [Vallar2023] dominated by Trapped Electron Mode instability → Suitable test-bed case!

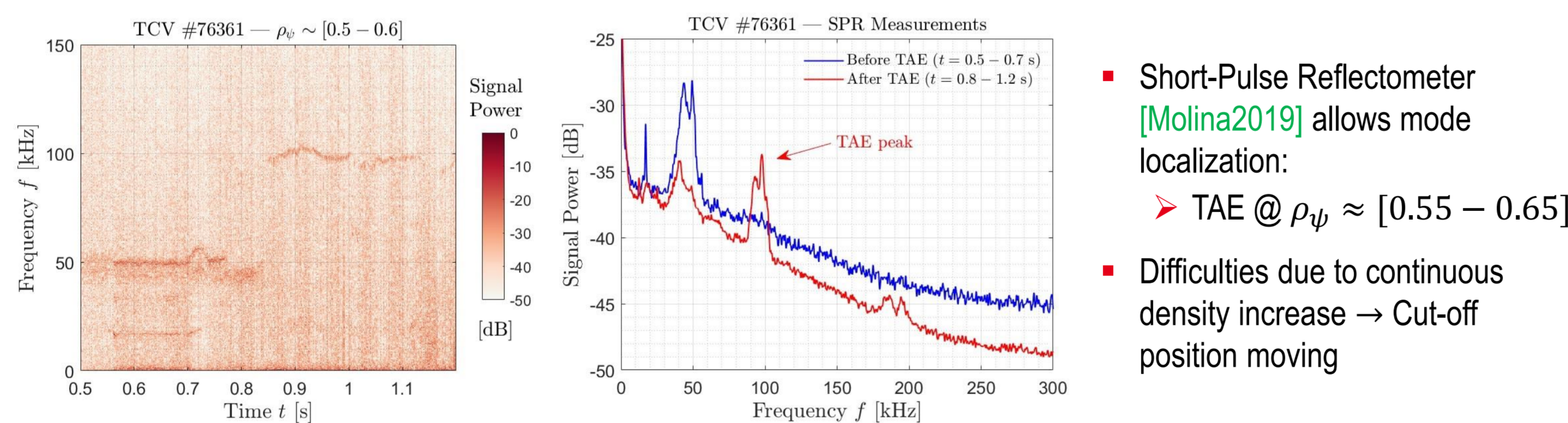
Observation of Fast-Ion-Driven Instabilities in TCV



- Other fast-ion-driven instabilities observed:
 - $n = -1$ @ ~ 15 kHz
 - $n = 0$ & $m = 1$ @ ~ 50 kHz (EGAM? [Geiger2020])
 - $n = 2$ EAE @ ~ 180 kHz
 - Other modes triggered by nonlinear coupling
- Unveiling P_{NBI} (or E_{FI}) thresholds → Different NBI power waveforms been adopted
- Step-like waveform (TCV #76361): defining quasi-steady phases for characterizing TAE impact on plasma properties & confinement

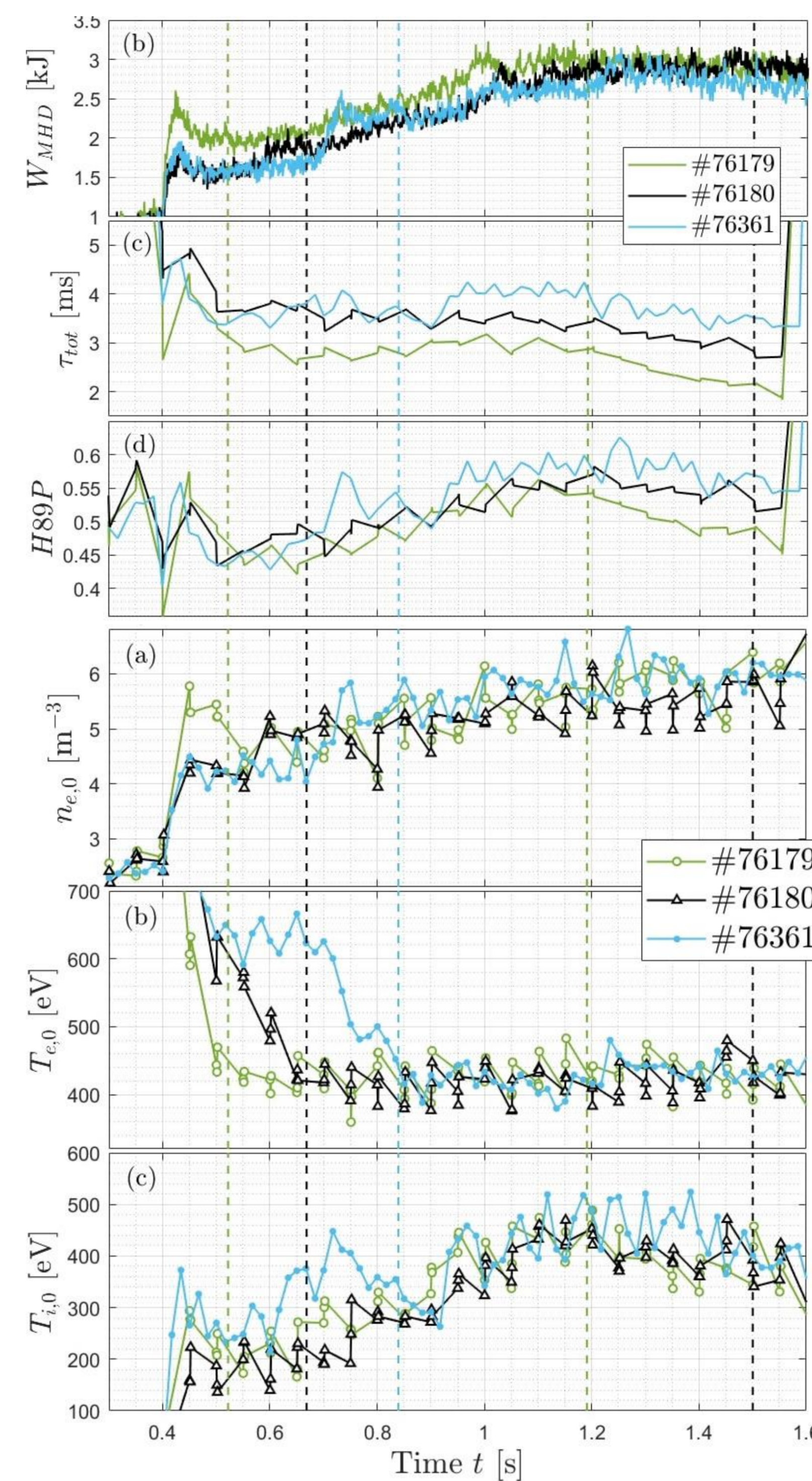


Reflectometer Study of Fast-Ion-Driven Instabilities



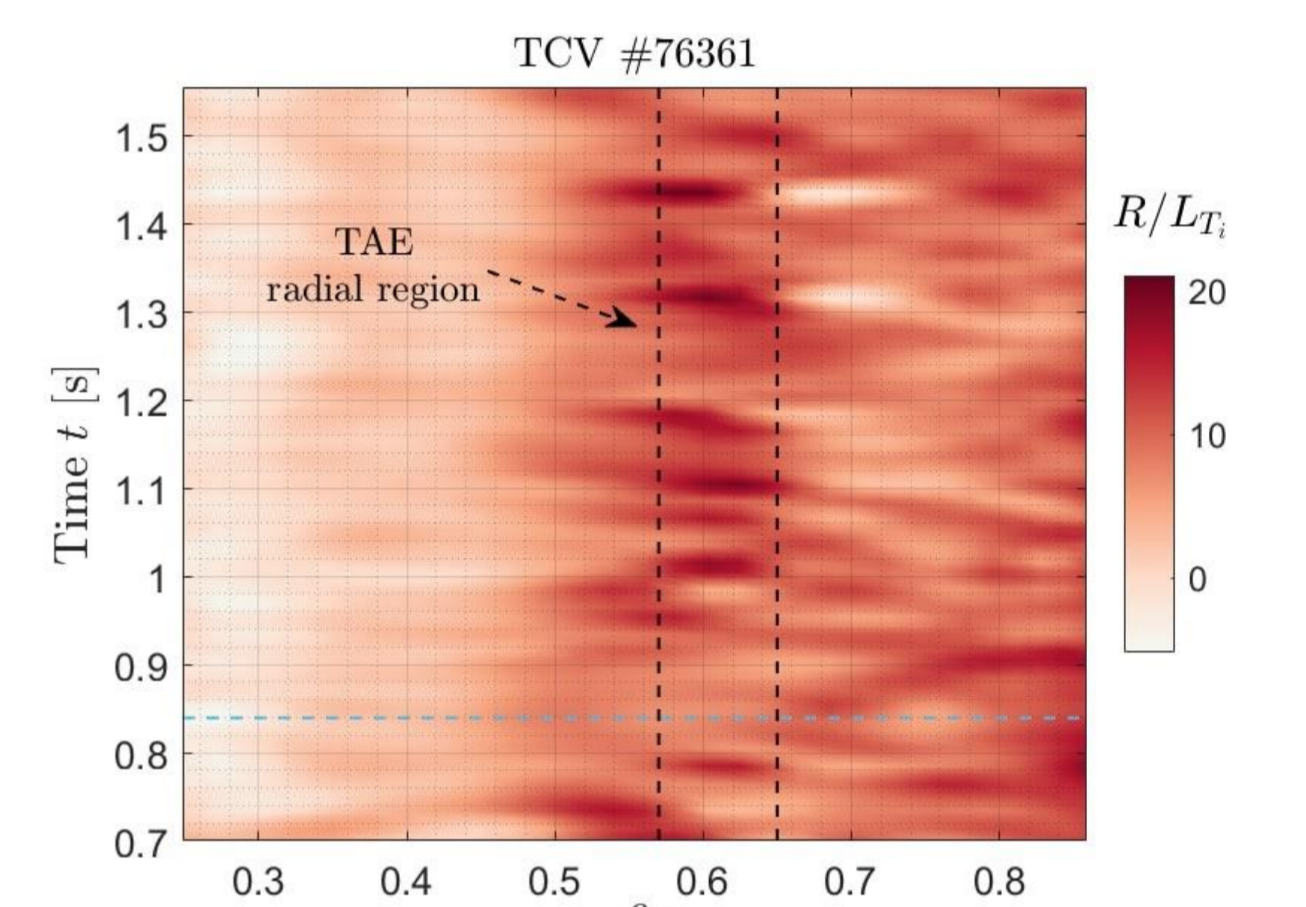
- Preliminary analyses on electron density fluctuations \tilde{n}_e → In the presence of TAE, \tilde{n}_e amplitude does not increase
- To be confirmed by more in-depth studies and gyrokinetic modelling:
 - Using method in [Krutkin2023] → Need for accurate electron density gradient values
 - ORB5 gyrokinetic global modelling addressing interplay between TAEs and micro-turbulence

TAE Impact on Global Plasma Confinement



- Various plasma parameters cross-analyzed during TAE phase (vertical dashed lines):
 - Increase of plasma energy content (W_{MHD}) up to the saturation (correlated with plasma elongation control failure)
 - Despite P_{NBI} increase, total energy confinement time τ_{tot} is stable
 - $H89 - P$ factor is increased during TAE phase and then saturates/decreases
 - Plasma density n_e increases due to unavoidable NBI fueling
 - Central ion temperature $T_{i,0}$ increases

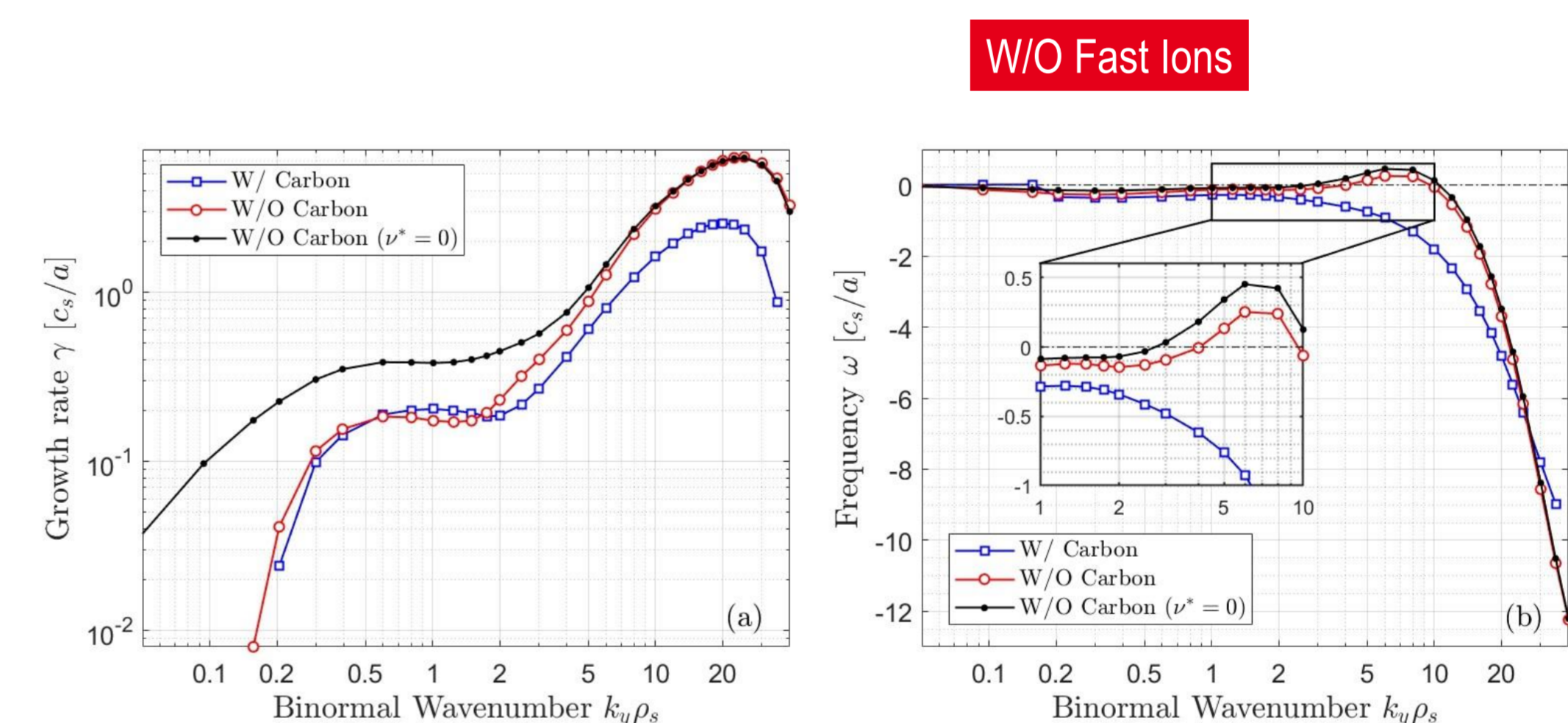
- The ion temperature gradient R/L_{Ti} is enhanced in the radial region of TAEs



The global plasma confinement is improved in conditions of unstable TAEs → Similar to what observed in the past [DiSiena2019, Mazzi2022]

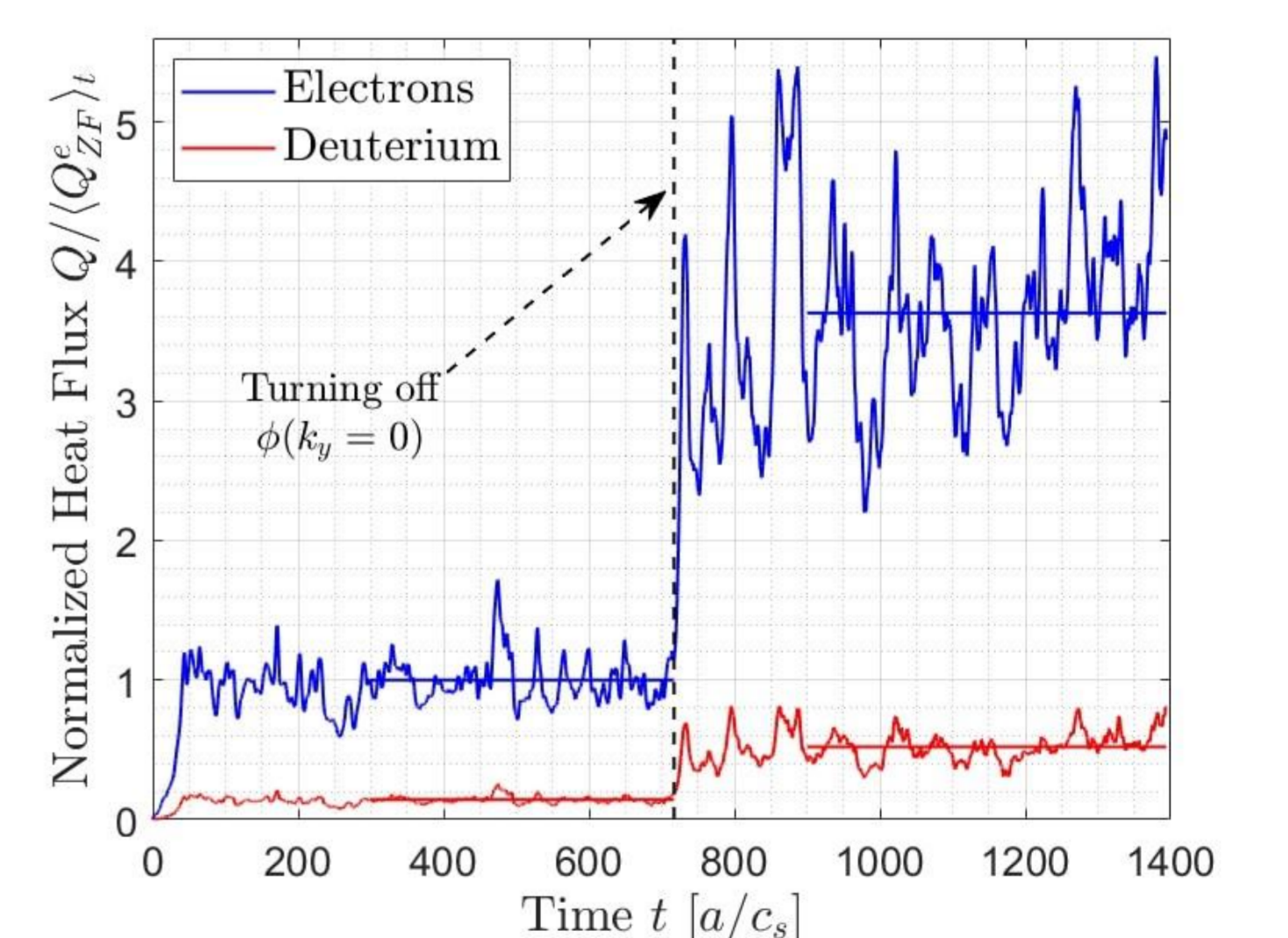
Local Gyrokinetic Studies

- Realistic local (flux-tube) gyrokinetic modelling: GENE [Jenko2000] of TCV #73461 @ $\rho_\psi = 0.65$ (TAE radial region)



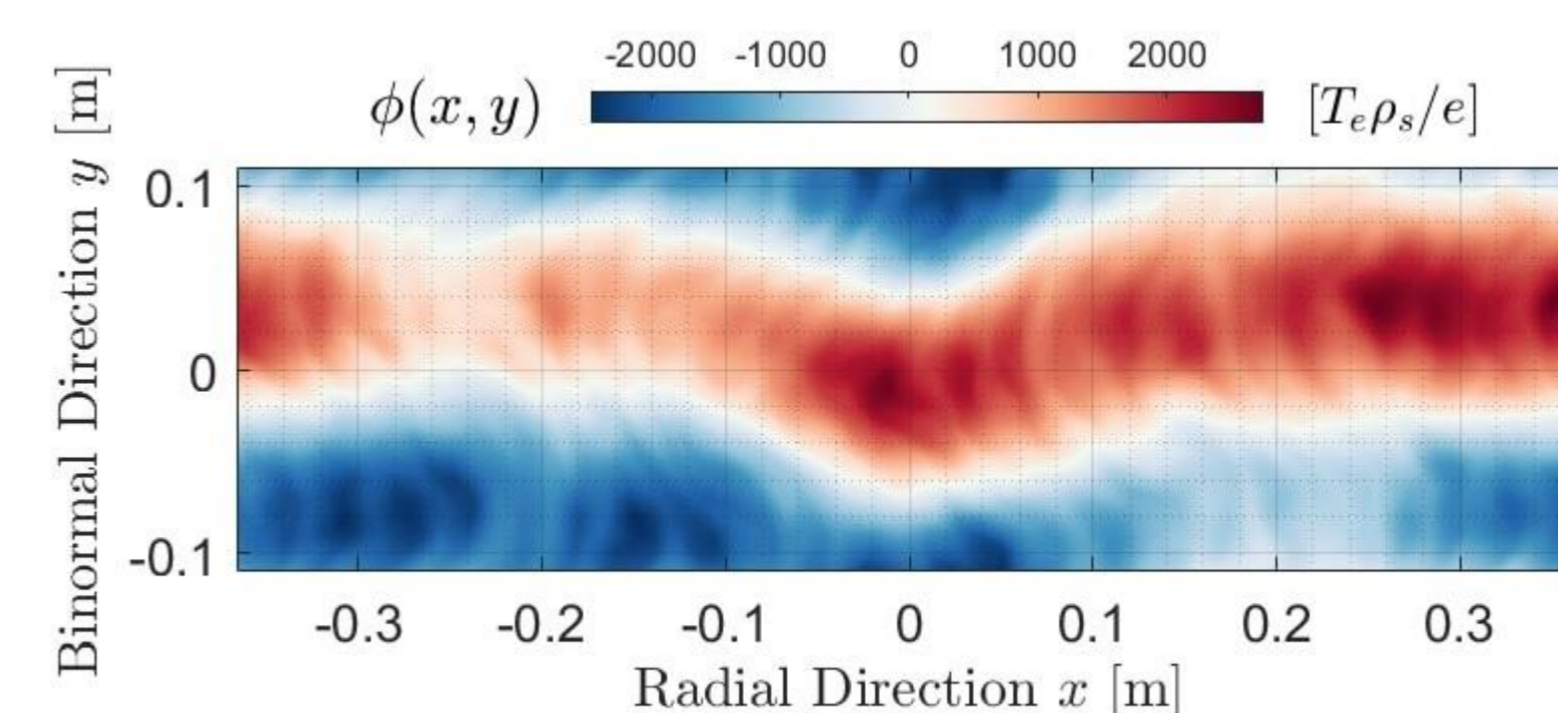
- Ion-scale region dominated by Trapped Electron Modes (TEMs)
- Ubiquitous modes unstable [Coppi1990] for $k_y \rho_s \sim 5 - 10$
- Electron Temperature Gradient (ETG) unstable in the electron-scale

- Nonlinear simulations → Retaining only ion-scale region ($k_y \rho_s < 1.45$) and without carbon impurities
 - Carbon stabilizes TEMs → Overestimation of fluxes without impurities [Merlo2015]
- Effects of Zonal Flows on ion-scale TEM-driven turbulence → When turned off, large increase ($\times 3.5$) of heat & particle fluxes
 - In this parameter range ($T_e/T_i > 1$) great effect of ZFs on TEMs [Lang2008]
 - If JET fast-ion beneficial effects holds → Possible reduction of turbulence and improvement of confinement



With NBI Fast Ions

- In linear spectra, fast-ion-driven modes unstable for $n = [1, 2, 3]$, but frequency @ $\sim 150 - 200$ kHz



- Nonlinear flux-tube simulations with fast-ion modes unstable:
 - Passing-through (streamer-like) structures appear even with box radial domain $>$ TCV size
- Need for global gyrokinetic modelling → ORB5 simulations ongoing

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