Preliminary analysis of JET 99896/5

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JET IMAS data prepared by Jorge Ferreira

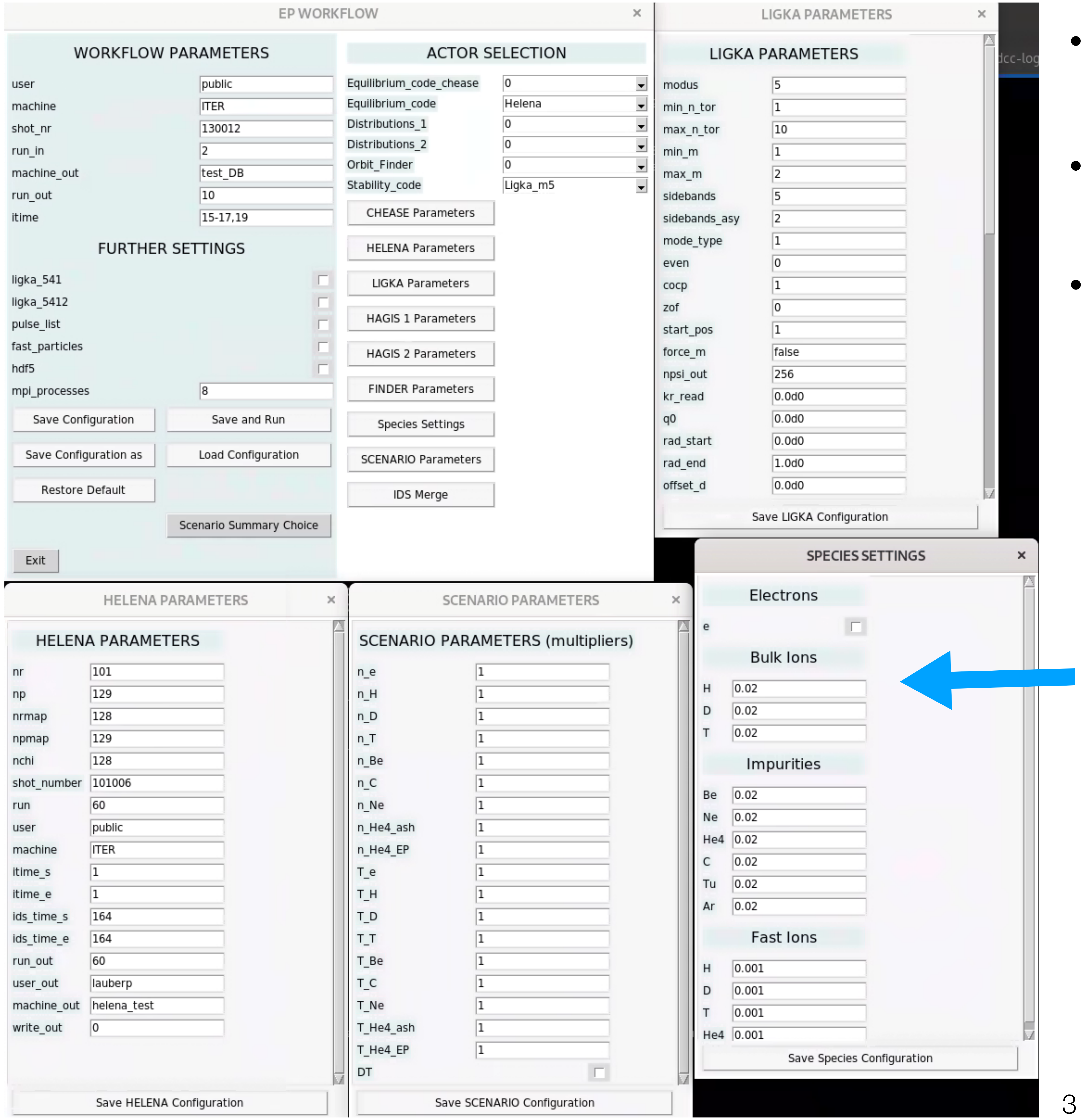
TSVV#10 meeting

22.1.2025

Overview

- Objectives:
    - perform time-dependent analysis on experimental DT data using IMAS-integrated EP-Stability-WF
    - validation of model hierarchy
    - get valuable insights into the dataset given by transport code; identify potential problems
    - identify with certainty effects that need to be studied (linear vs non-linear)
- Known problems:
    - No NBI distributions are present in the IDS (using Maxwellian equivalent)
    - treatment fast pressure perpendicular component (H) (19.02.2024 report JET data)

EP-Stability WF - Interface



WORKFLOW PARAMETERS

user	public
machine	ITER
shot_nr	130012
run_in	2
machine_out	test_DB
run_out	10
itime	15-17,19

FURTHER SETTINGS

ligka_541	☐
ligka_5412	☐
pulse_list	☐
fast_particles	☐
hdf5	☐
mpi_processes	8

ACTOR SELECTION

Equilibrium_code_chease	0
Equilibrium_code	Helena
Distributions_1	0
Distributions_2	0
Orbit_Finder	0
Stability_code	Ligka_m5

LIGKA PARAMETERS

modus	5
min_n_tor	1
max_n_tor	10
min_m	1
max_m	2
sidebands	5
sidebands_asy	2
mode_type	1
even	0
cocp	1
zof	0
start_pos	1
force_m	false
npsi_out	256
kr_read	0.0d0
q0	0.0d0
rad_start	0.0d0
rad_end	1.0d0
offset_d	0.0d0

HELENA PARAMETERS

nr	101
np	129
nrmap	128
npmap	129
nchi	128
shot_number	101006
run	60
user	public
machine	ITER
itime_s	1
itime_e	1
ids_time_s	164
ids_time_e	164
run_out	60
user_out	lauberp
machine_out	helena_test
write_out	0

SCENARIO PARAMETERS (multipliers)

n_e	1
n_H	1
n_D	1
n_T	1
n_Be	1
n_C	1
n_Ne	1
n_He4_ash	1
n_He4_EP	1
T_e	1
T_H	1
T_D	1
T_T	1
T_Be	1
T_C	1
T_Ne	1
T_He4_ash	1
T_He4_EP	1
DT	☐

Electrons

e	☐

Bulk Ions

H	0.02
D	0.02
T	0.02

Impurities

Be	0.02
Ne	0.02
He4	0.02
C	0.02
Tu	0.02
Ar	0.02

Fast Ions

H	0.001
D	0.001
T	0.001
He4	0.001

- The aim of the WF is to perform an automated linear stability analysis on different time slices of a projected scenario or reconstructed experimental equilibrium.
- First time-dependent workflow which makes use of the IMAS infrastructure and various codes.

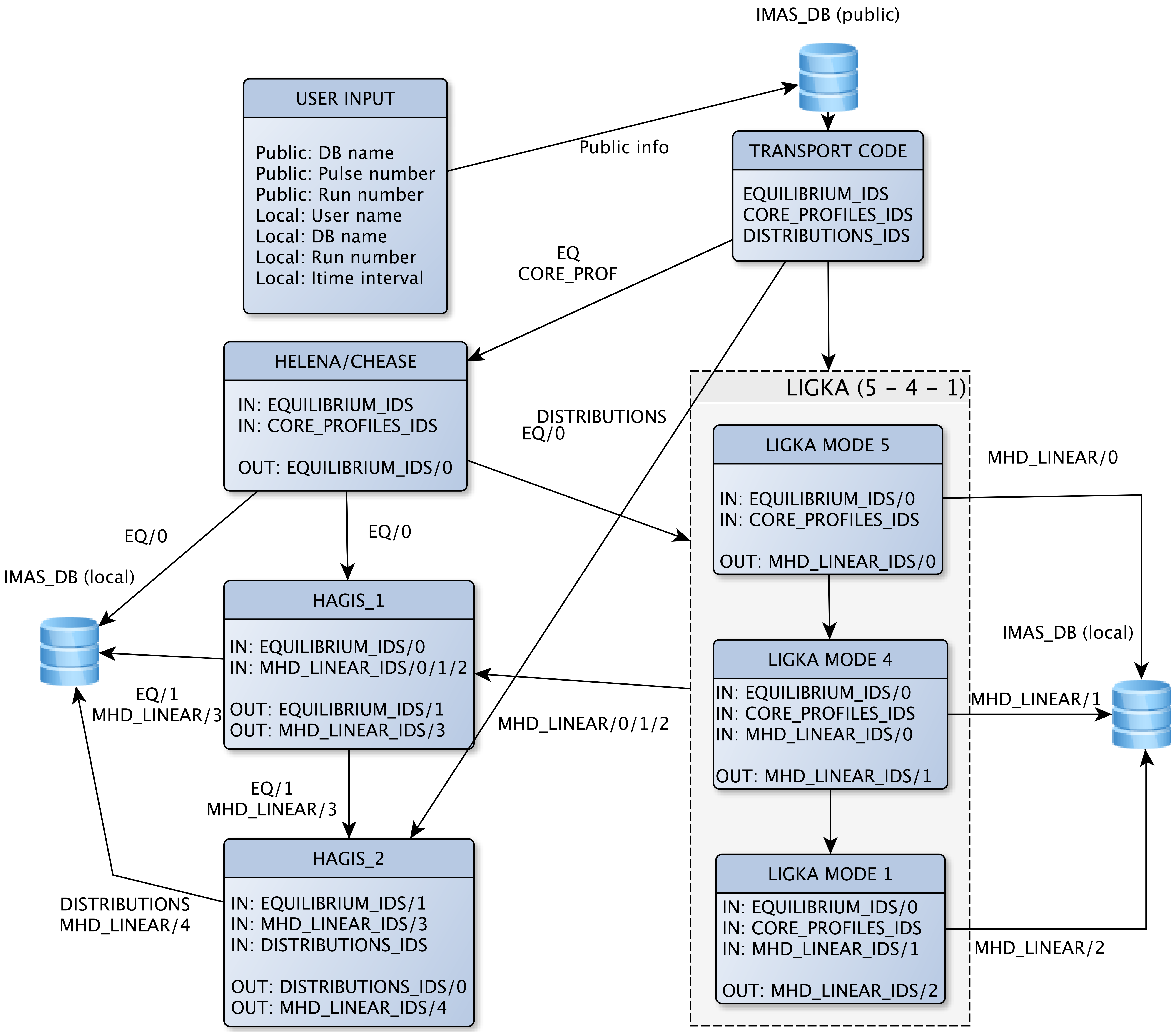
- **Scope:**
  - Connect the numerical tools with the data infrastructure (IMAS).
  - Facilitates retrieving/saving data from the DB through XML files.
  - Fast configuration of numerical tools.

Preparation for JET experiment analysis:

- generalisation to up to 5 EP species
- Fast Ion/Thermal/Total density checks
- extend LIGKA interface to more than 2 EP species
- various checks and tests introduced

https://indico.euro-fusion.org/event/2729/

EP-WF - Actor level



USER INPUT

Public: DB name
Public: Pulse number
Public: Run number
Local: User name
Local: DB name
Local: Run number
Local: ltime interval

TRANSPORT CODE

EQUILIBRIUM_IDS
CORE_PROFILES_IDS
DISTRIBUTIONS_IDS

HELENA/CHEASE

IN: EQUILIBRIUM_IDS
IN: CORE_PROFILES_IDS

OUT: EQUILIBRIUM_IDS/0

HAGIS_1

IN: EQUILIBRIUM_IDS/0
IN: MHD_LINEAR_IDS/0/1/2

OUT: EQUILIBRIUM_IDS/1
OUT: MHD_LINEAR_IDS/3

HAGIS_2

IN: EQUILIBRIUM_IDS/1
IN: MHD_LINEAR_IDS/3
IN: DISTRIBUTIONS_IDS

OUT: DISTRIBUTIONS_IDS/0
OUT: MHD_LINEAR_IDS/4

LIGKA (5 – 4 – 1)

LIGKA MODE 5

IN: EQUILIBRIUM_IDS/0
IN: CORE_PROFILES_IDS

OUT: MHD_LINEAR_IDS/0

LIGKA MODE 4

IN: EQUILIBRIUM_IDS/0
IN: CORE_PROFILES_IDS
IN: MHD_LINEAR_IDS/0

OUT: MHD_LINEAR_IDS/1

LIGKA MODE 1

IN: EQUILIBRIUM_IDS/0
IN: CORE_PROFILES_IDS
IN: MHD_LINEAR_IDS/1

OUT: MHD_LINEAR_IDS/2

Added in preparation for JET experiment analysis:

- LIGKA extensive modification and testing regarding multiple species of fast/thermal ions.
- Given the high pressure from fast ions, some solvers (kinetic continuum, global solver) had to be tuned (e.g. numerical settings; complex plane integration domains,…)
- Preparing ATEP for JET data

- **Maintenance cycle of actors + WF:**
- **Actors are self contained codes that can act independently or as part of a workflow.**
- **They are continuously tested and maintained via versions (different modules in sdcc/gw)**
- **On top of that we have the EP-Stability-WF integrated testing.**
- **When testing the wf, we also test the integration of LIGKA + HELENA/CHEASE inside the WF (2x testing for actors)**
- **Testing happens automatically at every push of every piece of code (via automated bamboo tests)**

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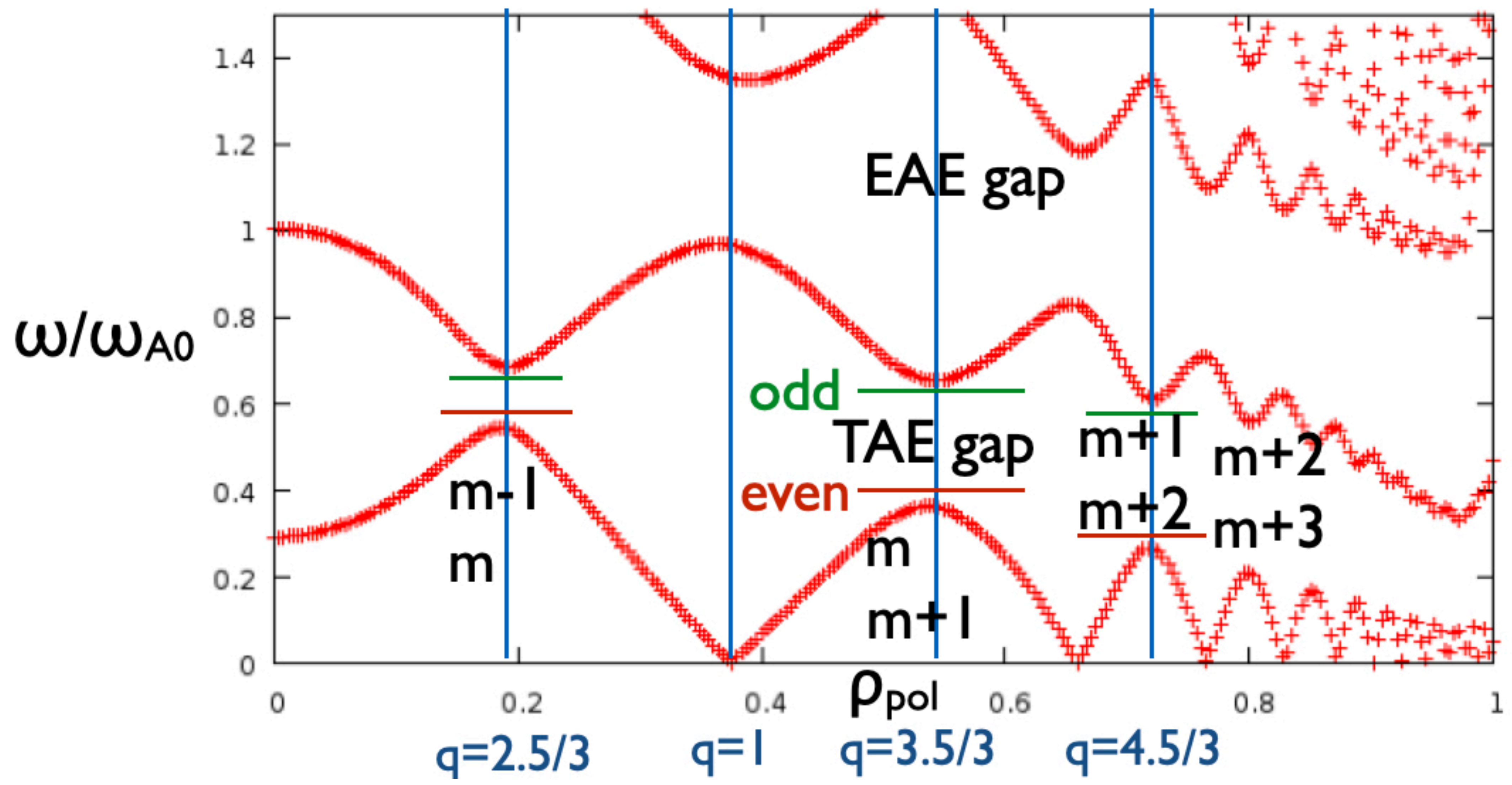
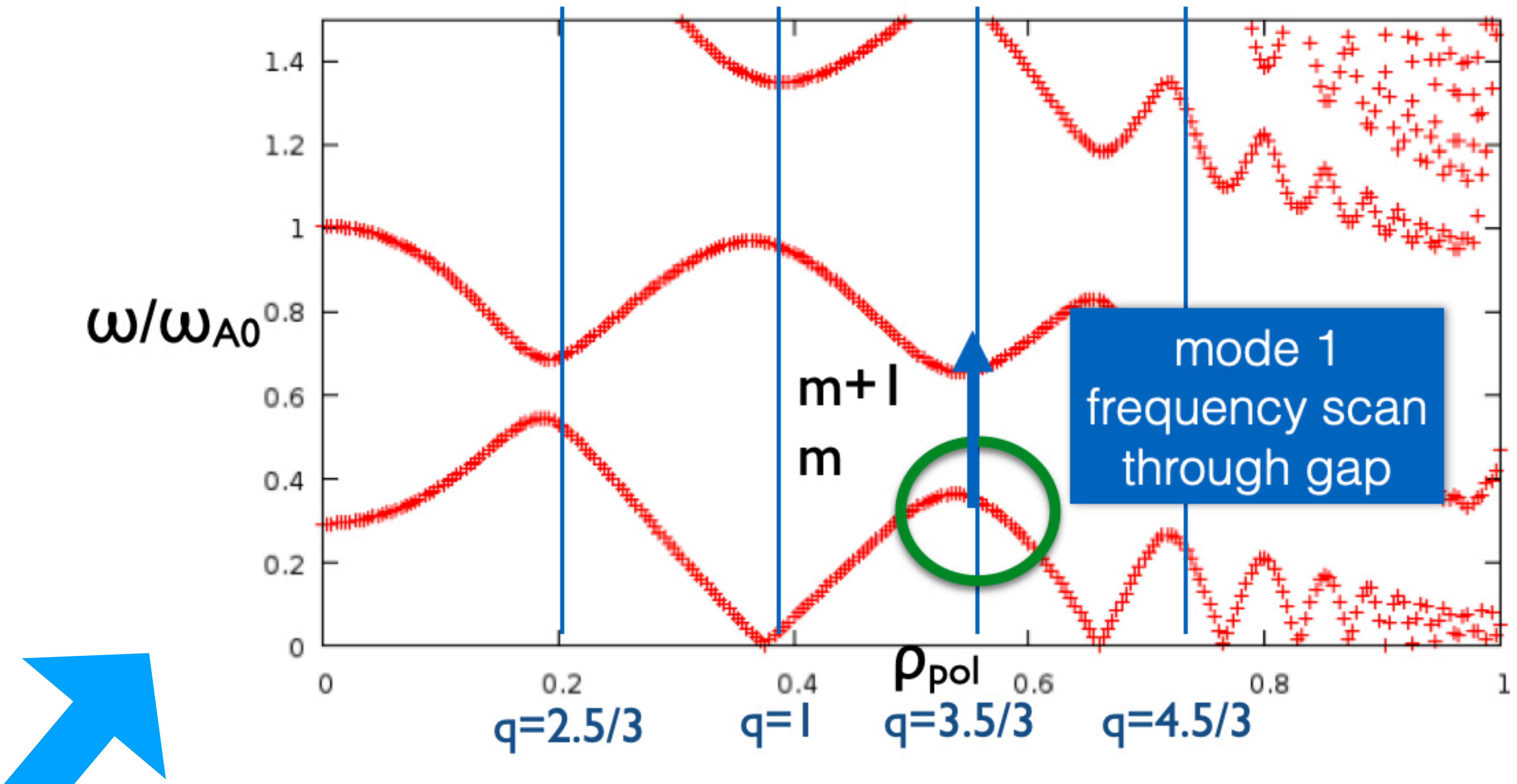
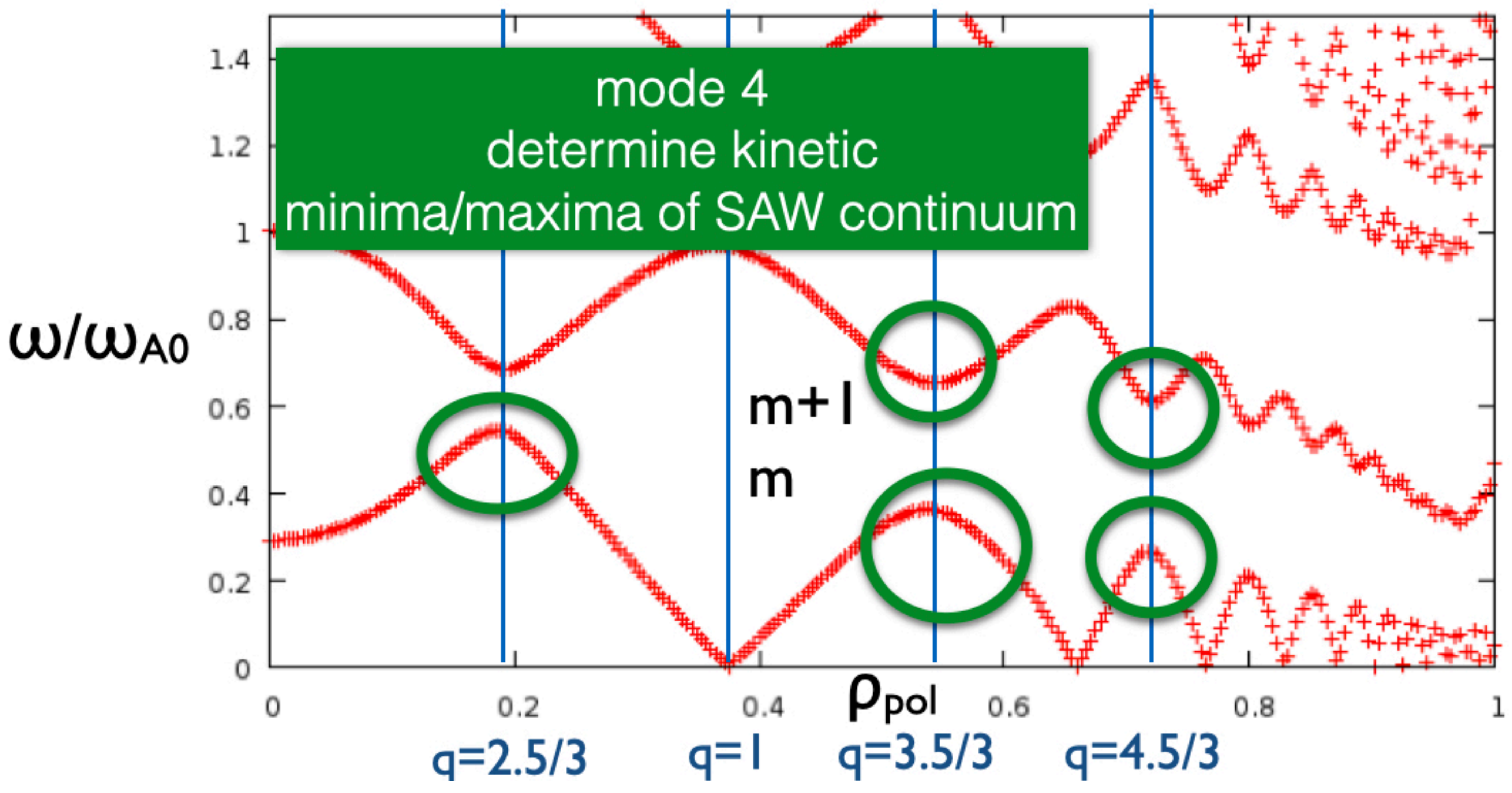
LIGKA - summary

q=(m+1/2)/n

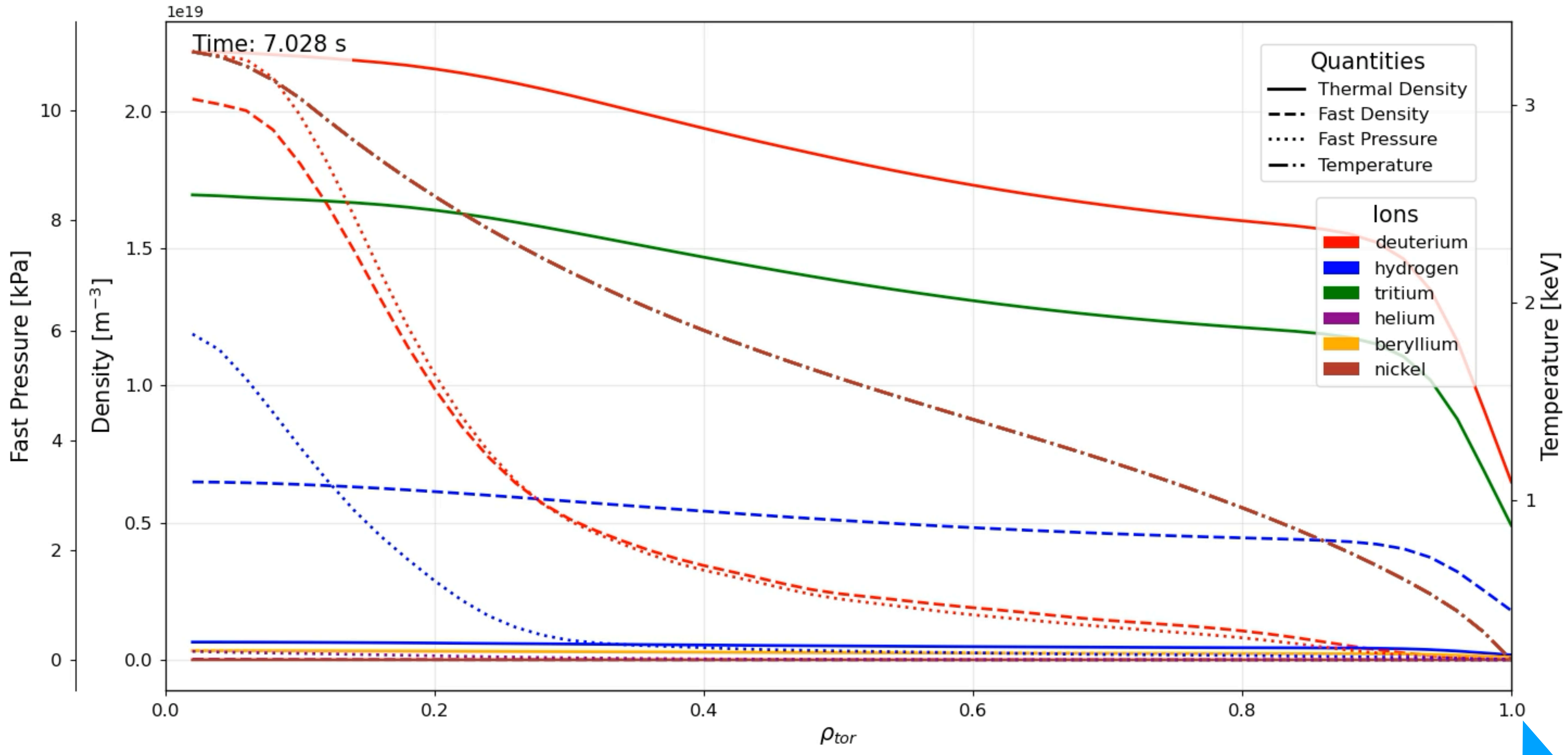




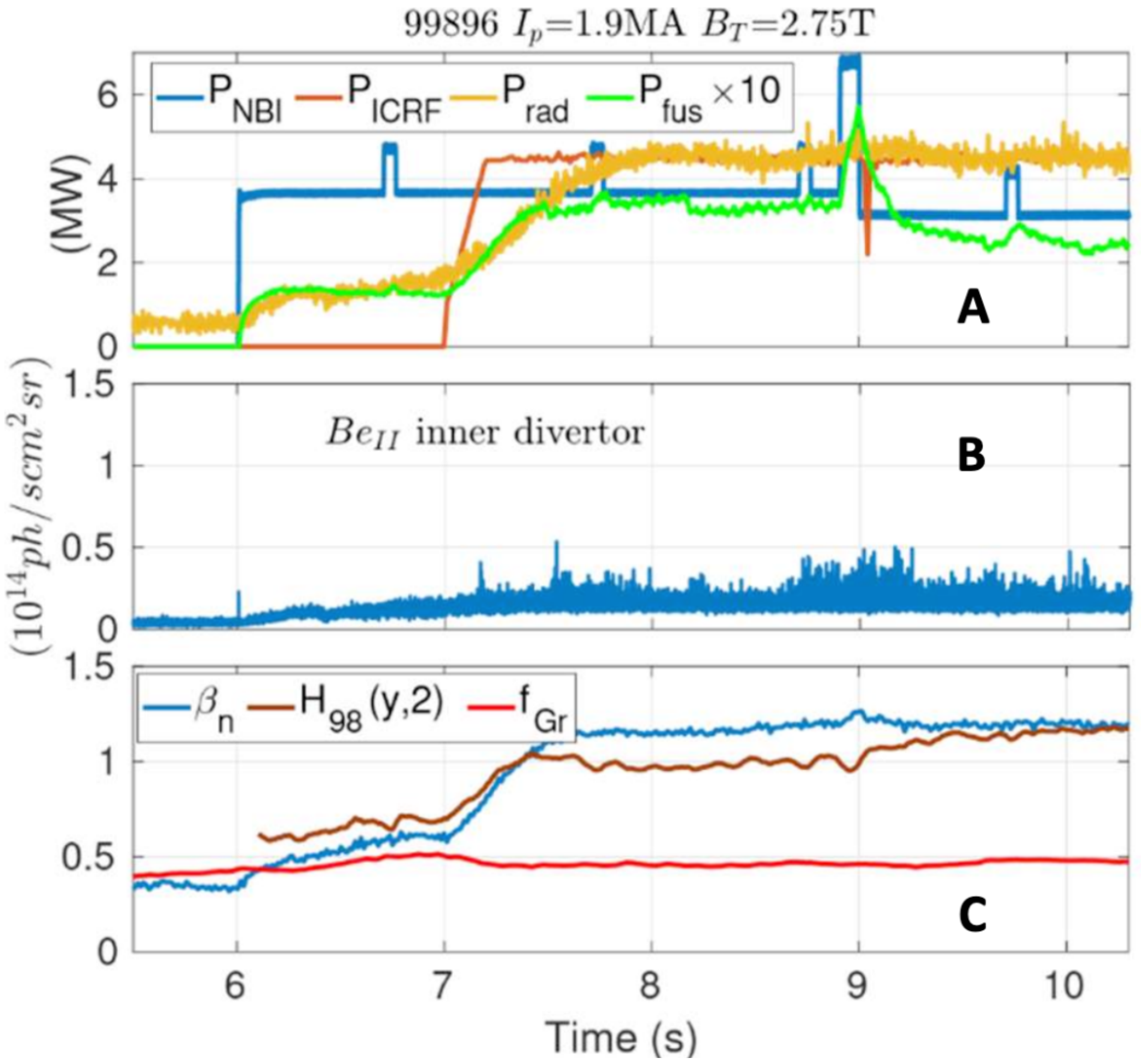


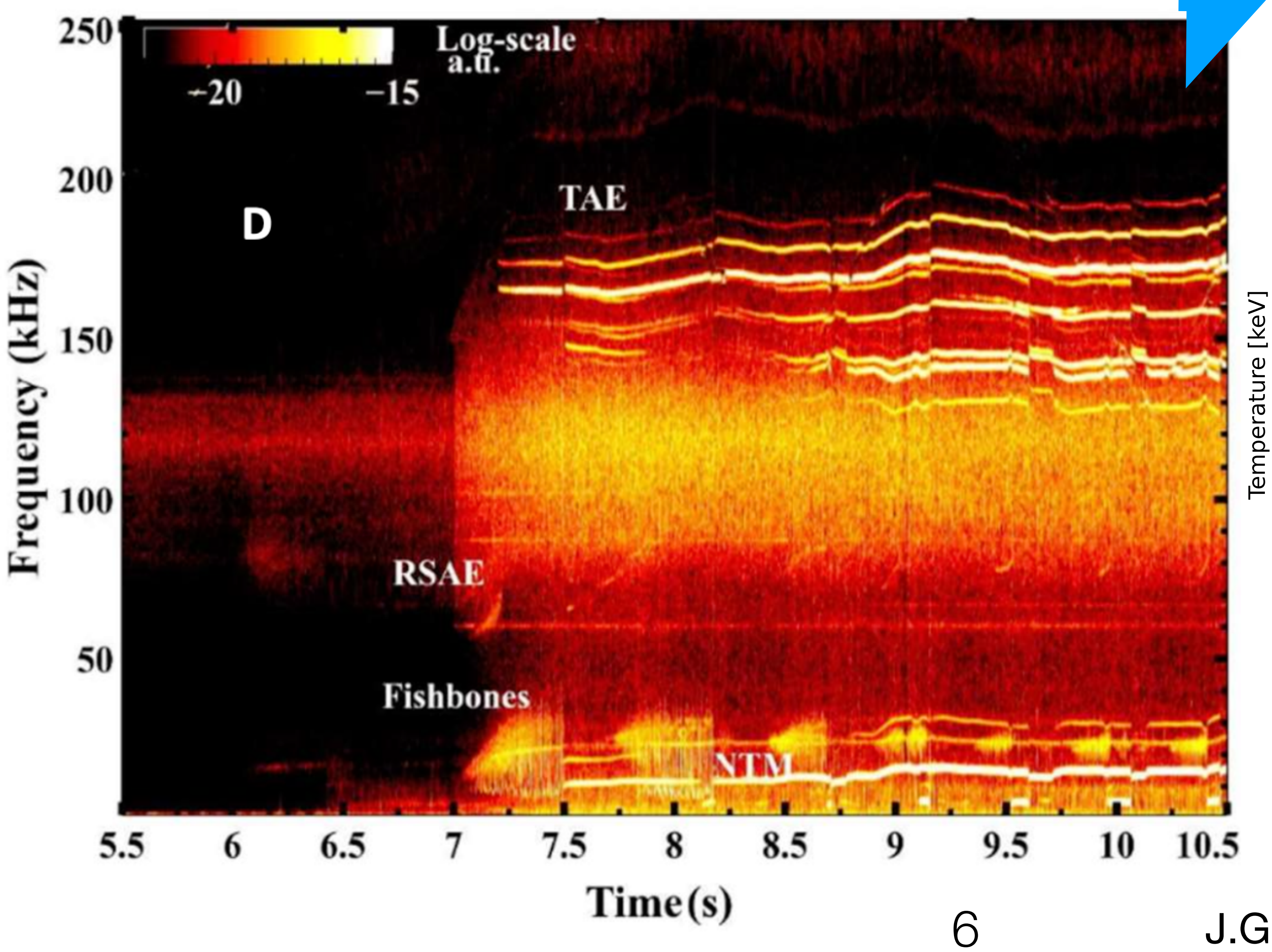
- LIGKA: solves linearized gyrokinetic equations to obtain eigenvalues and eigenfunctions.
  - Model 5 (analytical): local analytical estimates of various AEs properties
  - Model 4 (local): local analytical dispersion relation for one AE (n,m-pair), giving a good estimate for ion LD (Landau Damping) and local electron LD.
  - Model 1 (global): find linear properties of AEs, i.e. the location of the global AE in the gap.
  - Model 2 (global, refined): find the phase jump during the frequency scan, more accurate growth/damping rate.
  - Model 6/3: reduced MHD/kinetic spectrum.

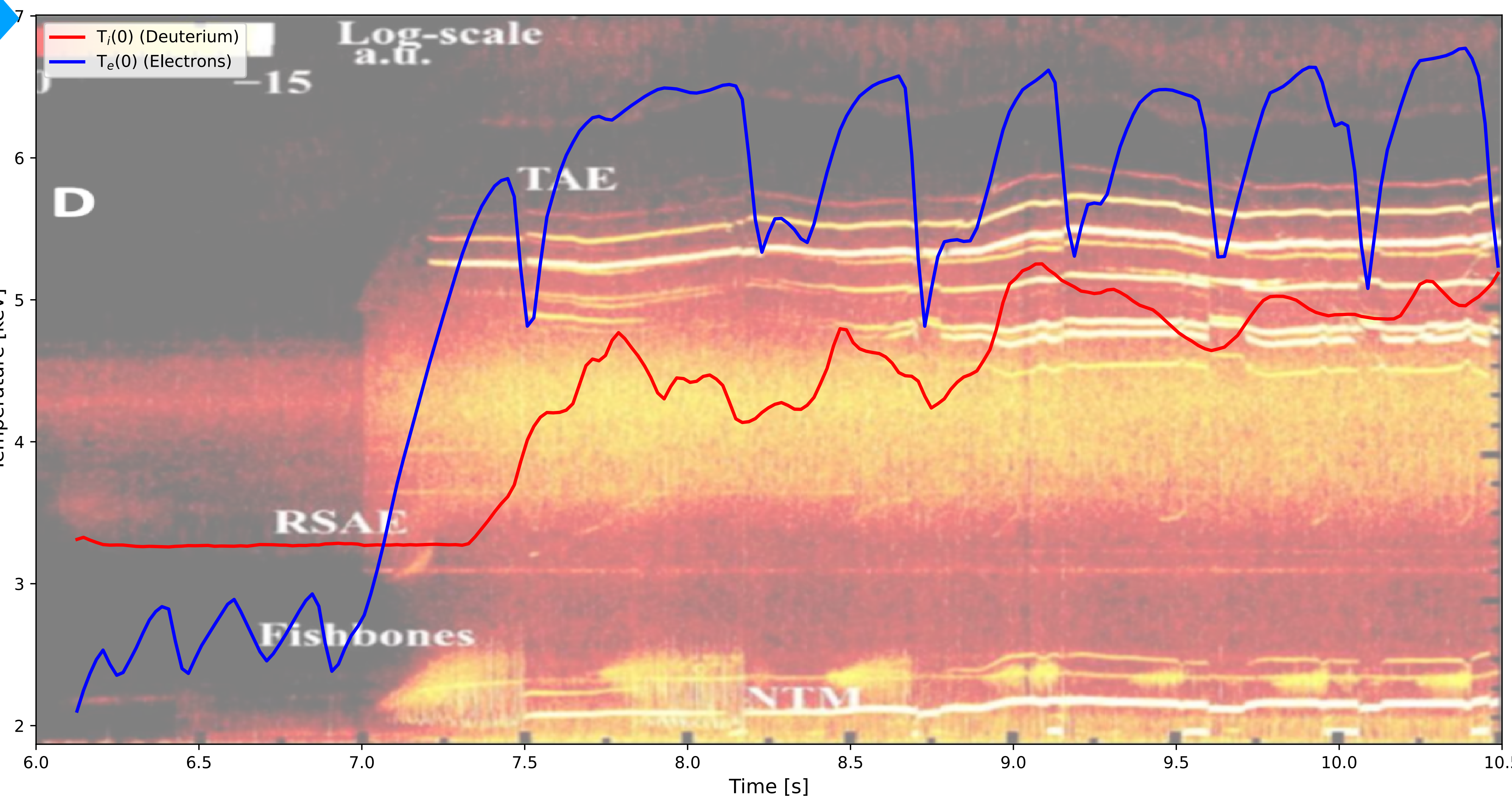
JET - DT - 99896/5



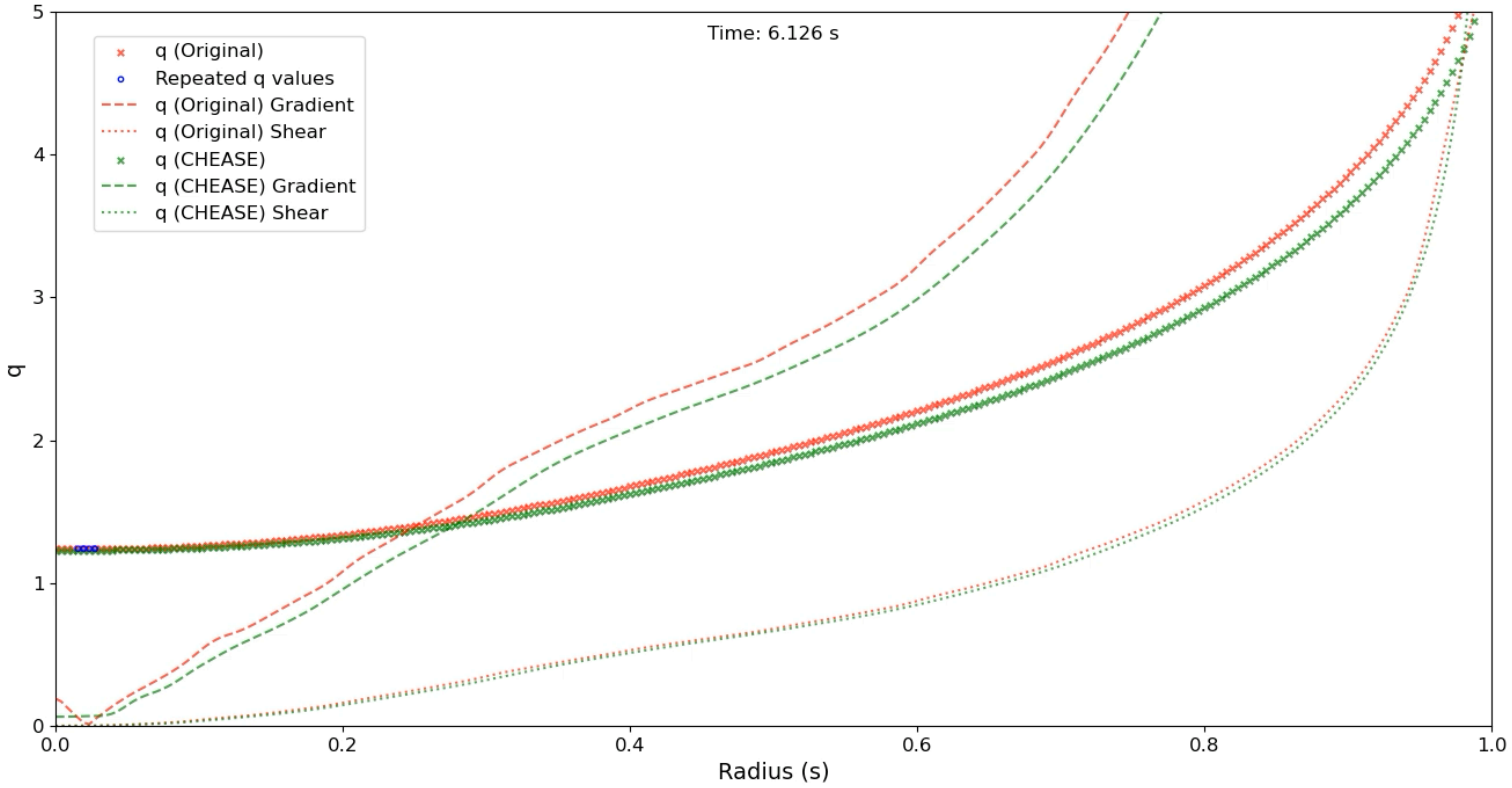
- 50-50 D-T ~58/42
- ICRF = 4.5MW. NBI ~ 3.5MW, D beams < 9 s and T > 9s. P_fusion ~ 0.5MW
- T_i is very transient even during 1 sawtooth crash comparison (8.3s-8.7s).
- T_i already decreases before the crash at 8.75s
- The mode activity is increased (more TAEs+larger fishbones: not only stabilizing)
- Use linear time-dependence analysis to see linear vs non-linear effects



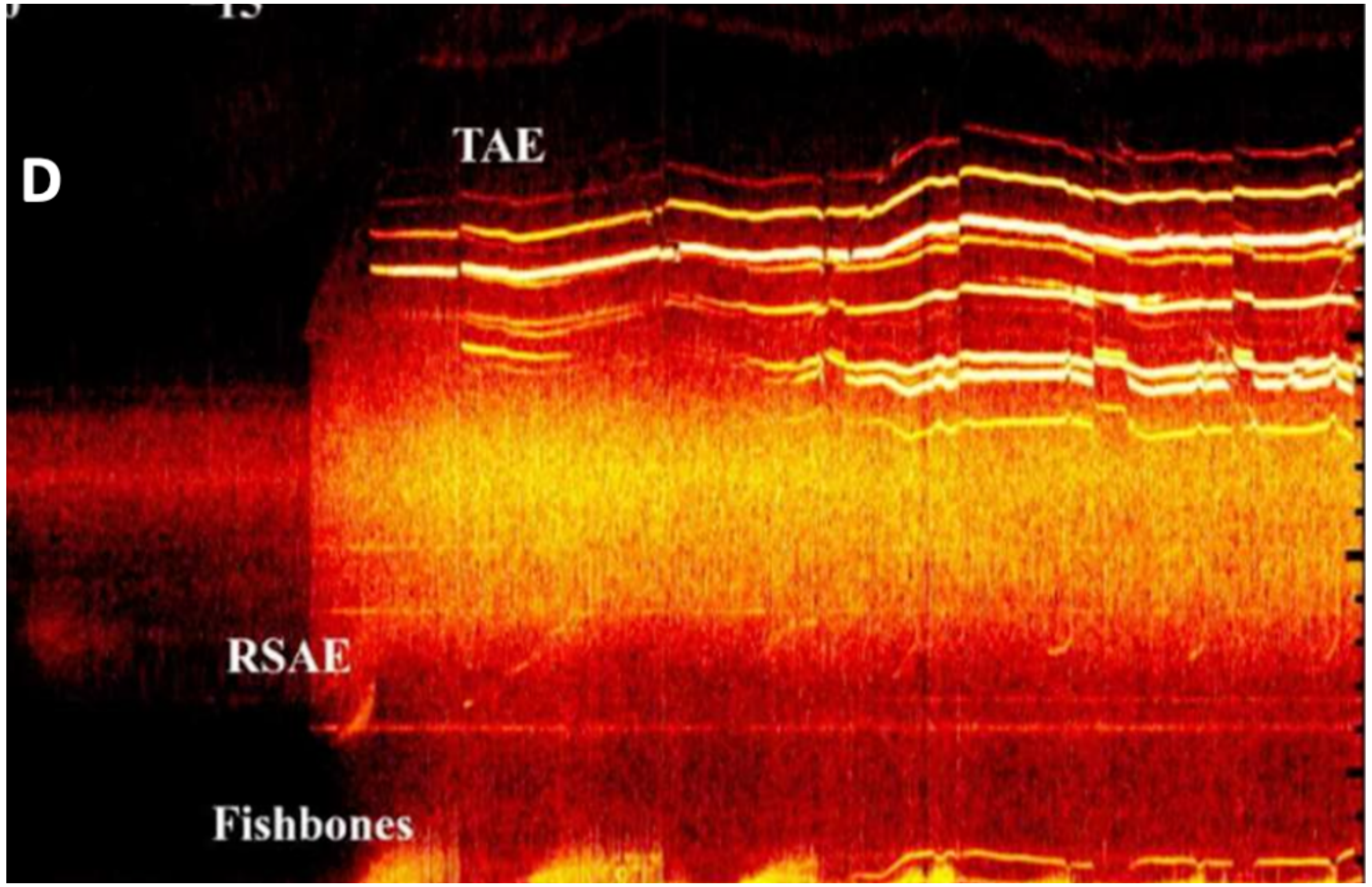




J.Garcia et.all. Nature 2024



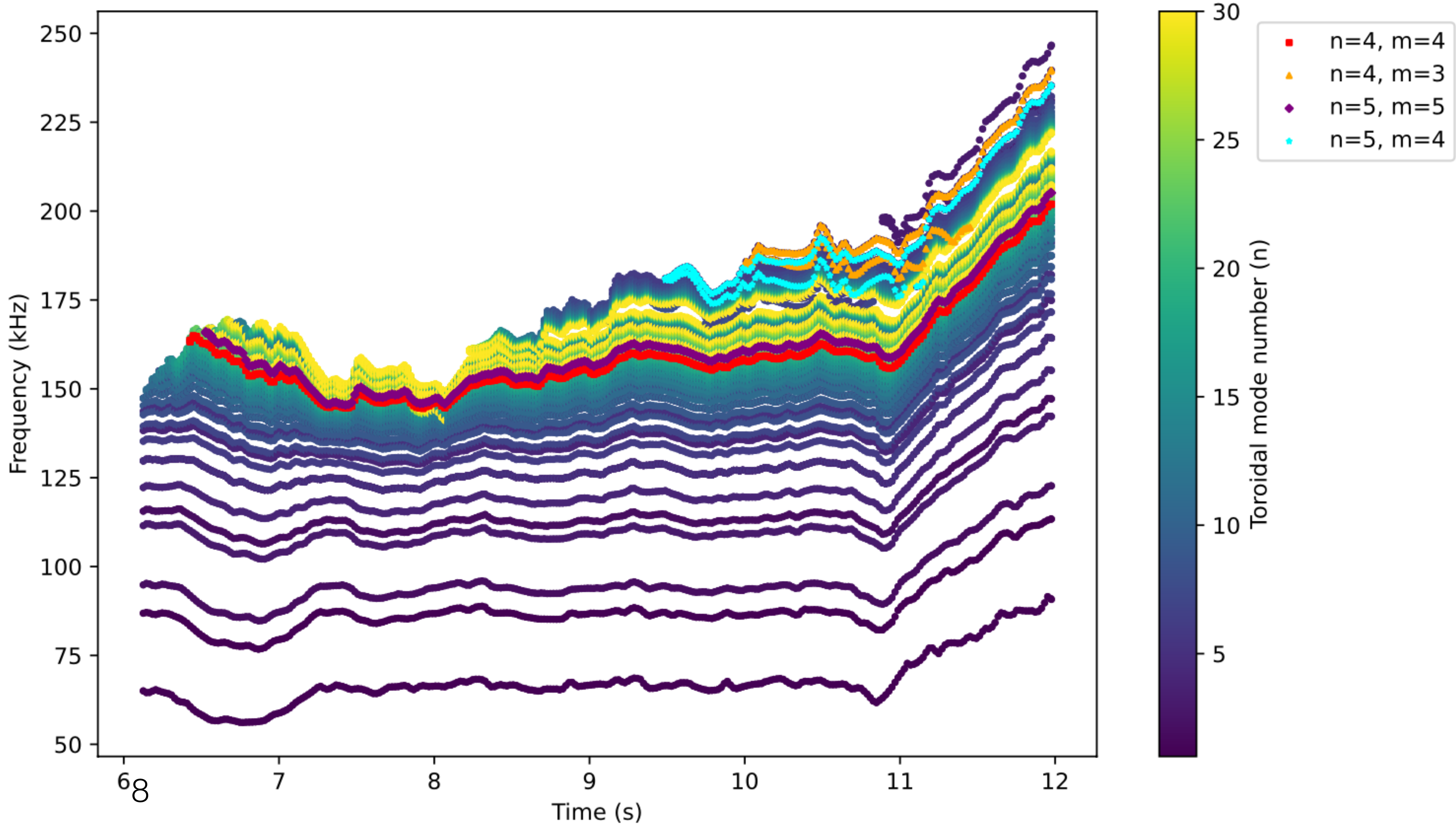
- q-profile is decreasing during the discharge
- slightly reversed q-profile
- no sawtooth dynamics included
- we cannot expect direct correspondence to the experiment: q=1 constrained equilibria are needed



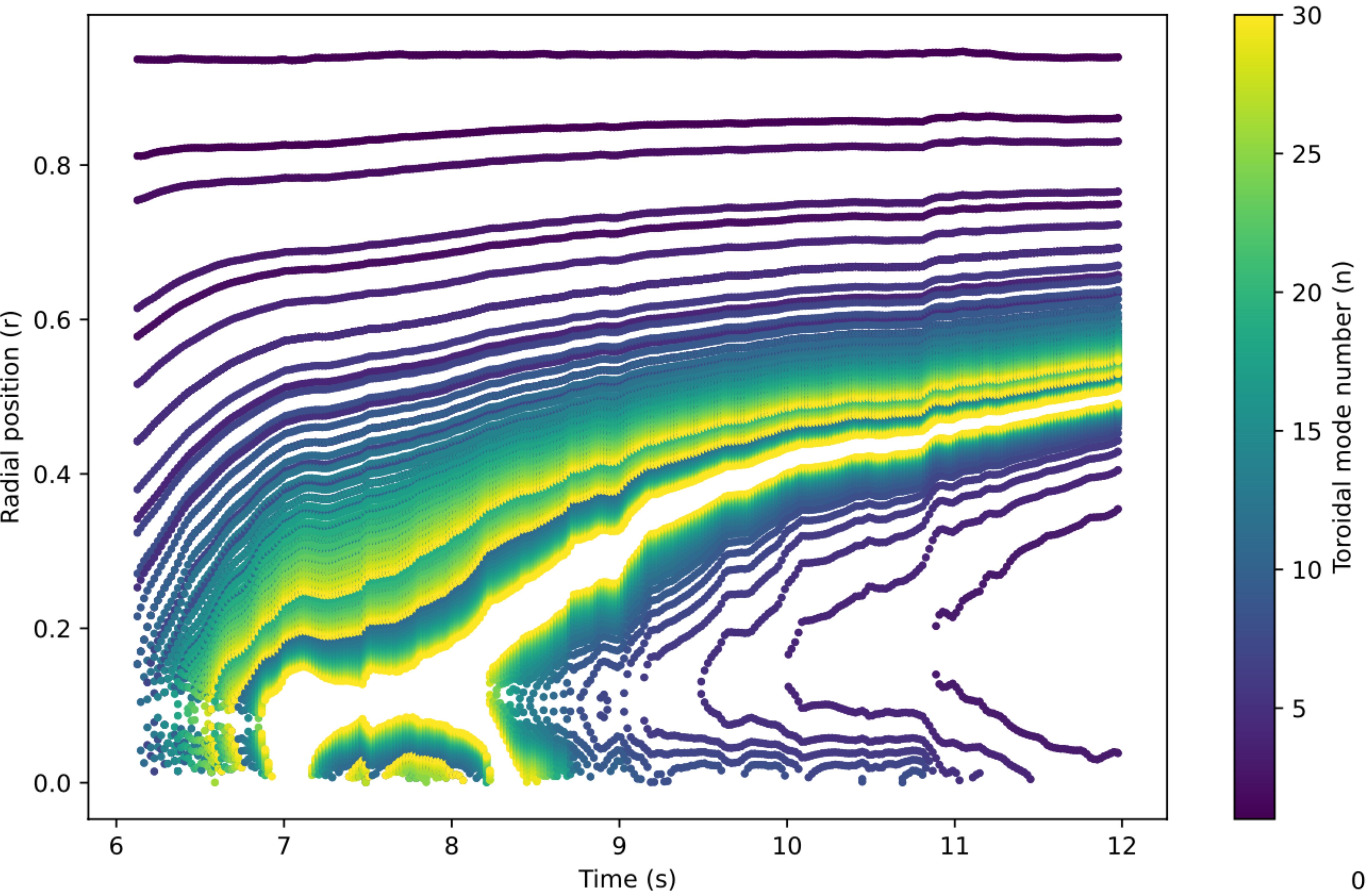
local analytical model: TAE frequency

- n = 1…30
- m = n-1…n+3
- number of modes = 32k (45 min runtime (including equilibrium calculations)
- frequencies roughly constant; after 11s Alfven frequency decreases, so the mode frequency increases
- q_TAE = (m+1/2)/n

- n,m = 4,4 and 5,5 exist across the discharge
- (4,3) and in general (n, n-1) due to the q profile will not exist everywhere

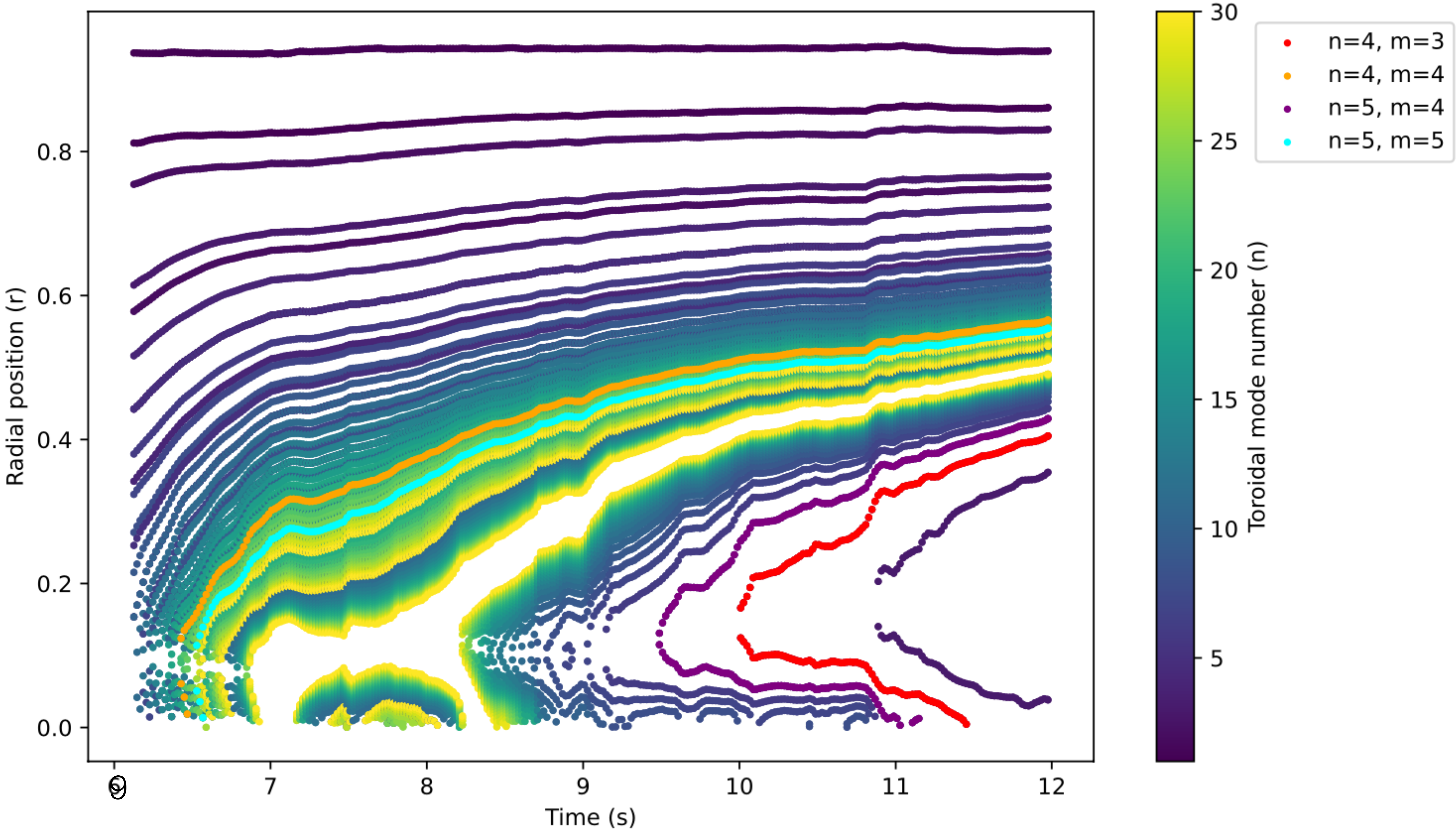


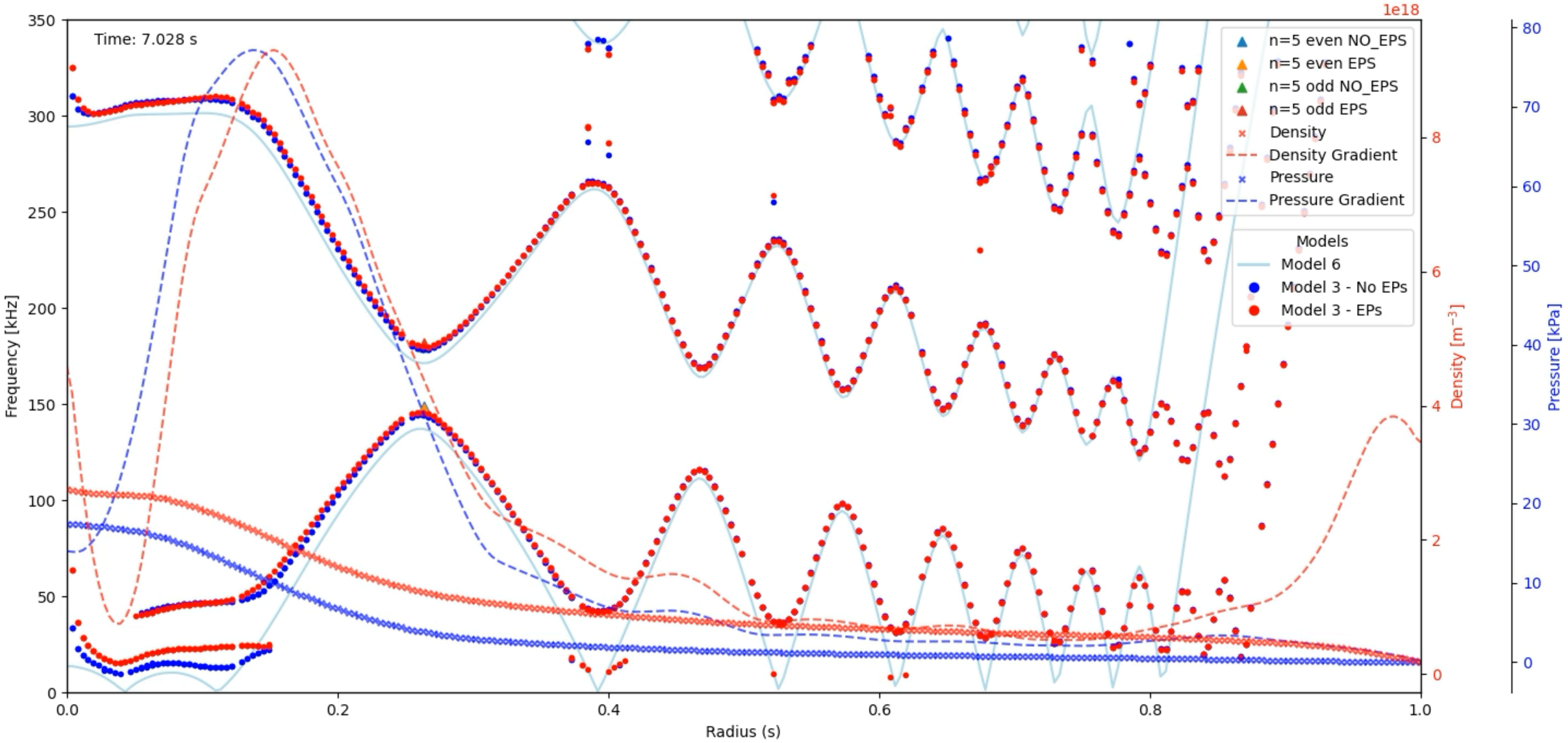
local analytical model: TAE radial location



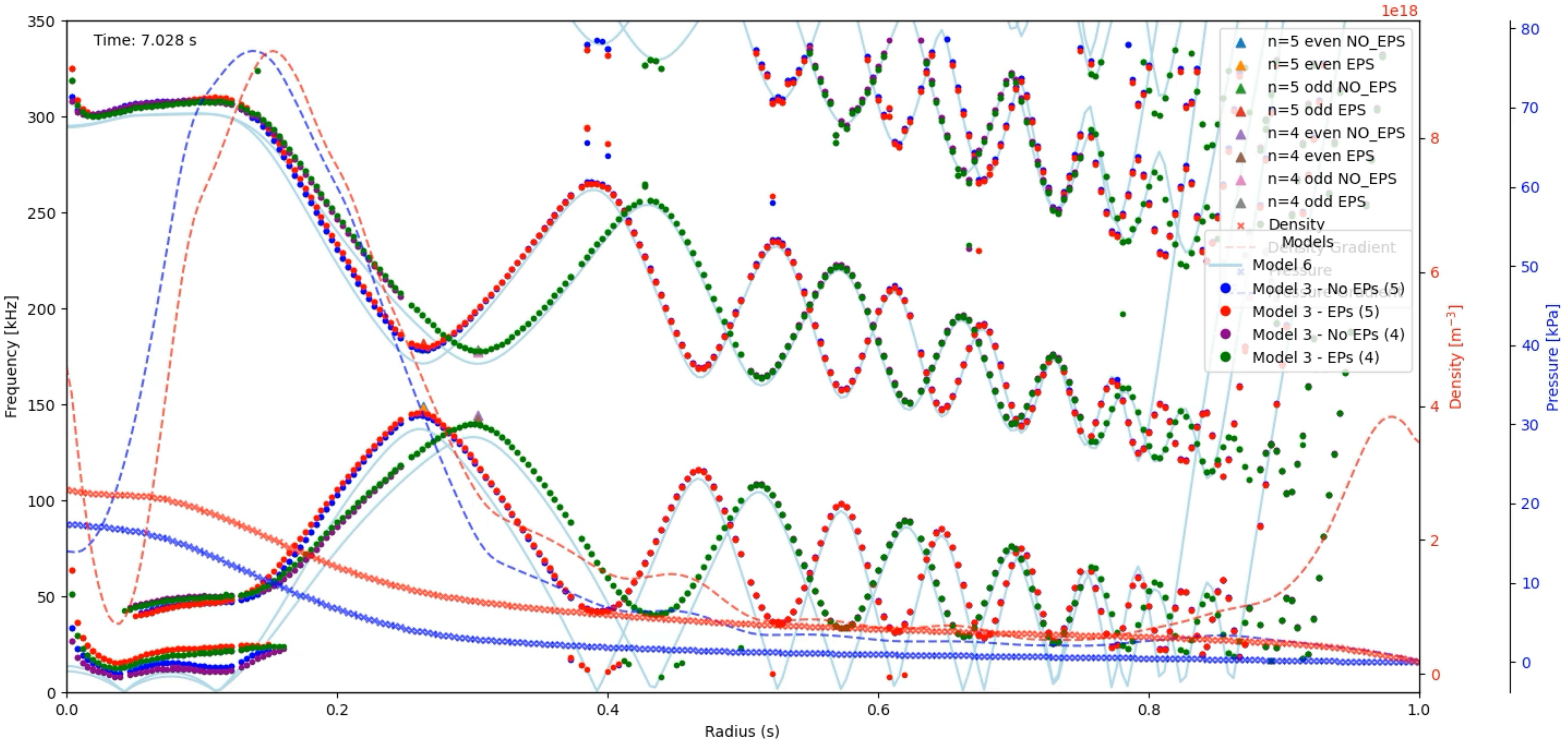
- The analytical model determines the middle of the continuum TAE gap
- The q=1 surface shifts during the discharge, and it can be seen going away from the core and towards the middle of the plasma.
- Different branches of the same modes are visible near the core, where q profile is non-monotonic.

- radial location of the n/m=4/4 and 5/5 modes (light blue lines) - and all other TAEs move radially outwards, away from steep EP gradient region: contradiction to stronger mode activity in second phase of discharge



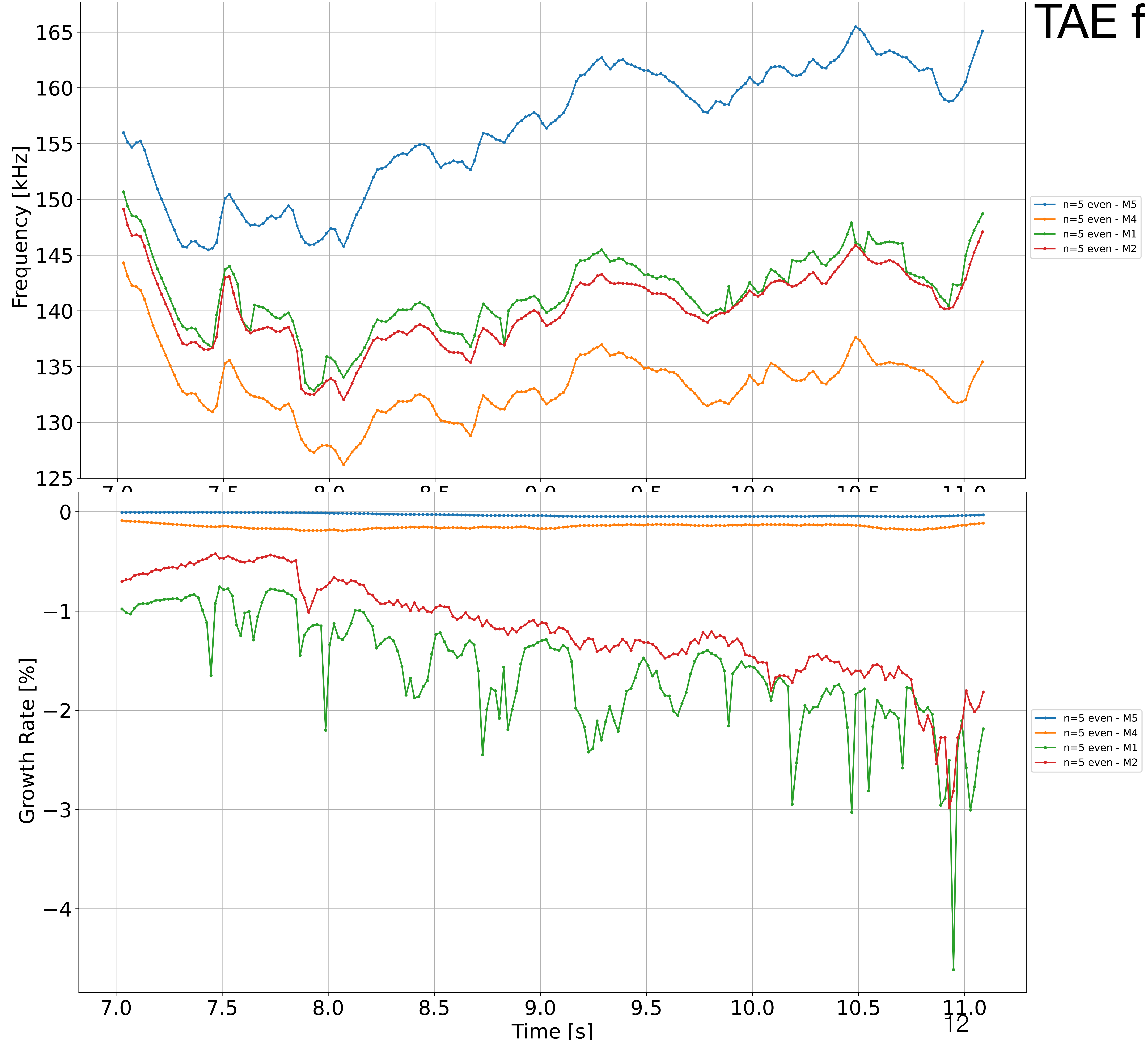


- Shifting of the gap (modes) away from the core is visible.
- Modes of the kind (n,m) = (n,n) like (5,5) even and odd exist during the whole discharge in the highest EP gradient region
- Closing of the (n, n-1) gap is evident once kinetic continuum calculation (model 3) is run with fast ions.



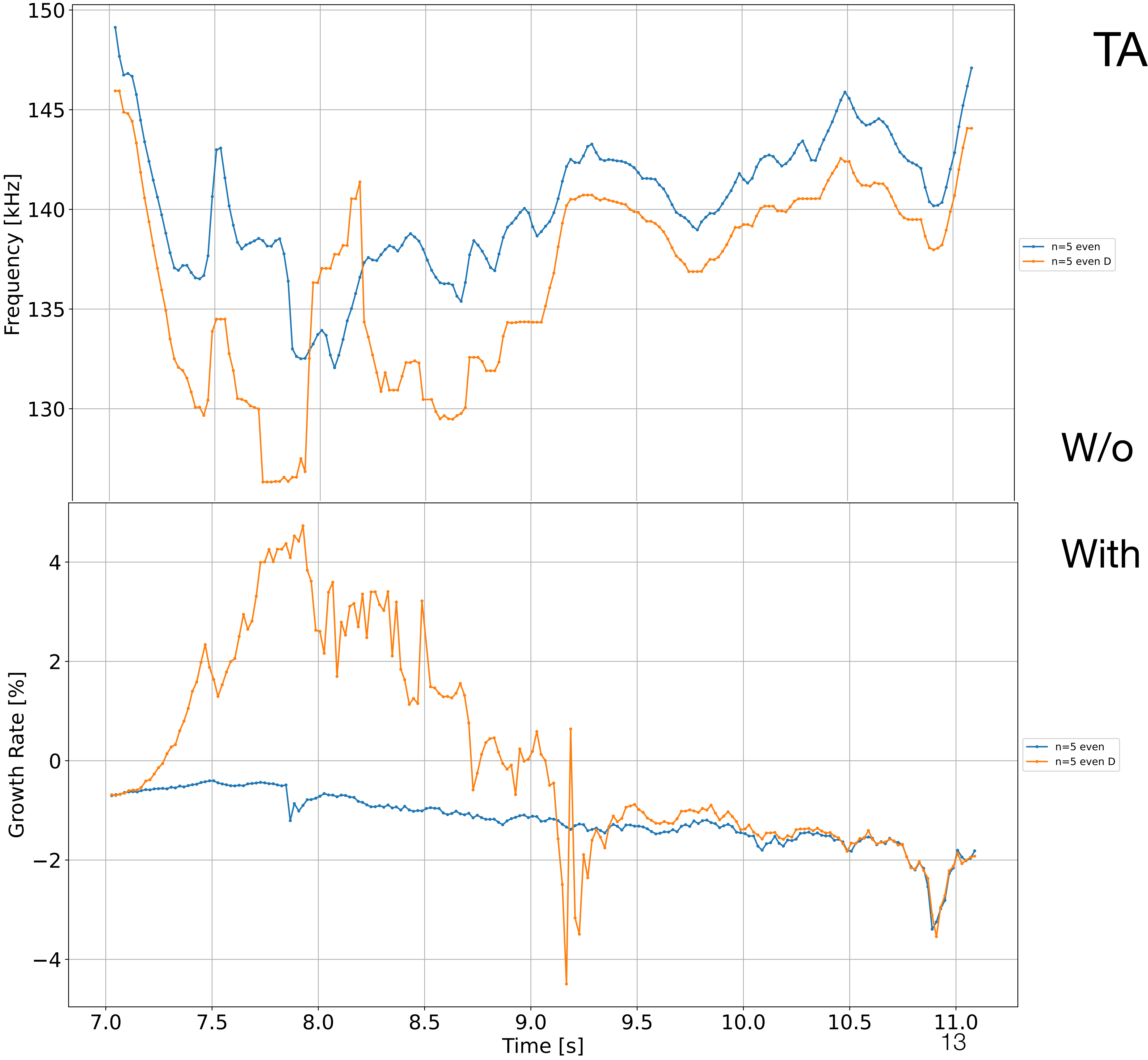
- The same behavior is observed for n=4
- The difference between n=4 and n=5 is approximately 5 kHz (different radial location and thus different Alfven velocity, q)
- The difference between the location of the modes inside is shrinking (shear is increasing: closer distance of TAE locations)

TAE frequency and damping w/o EPs



- even TAE frequency as calculated with different LIGKA models:
  - blue: analytical middle of the TAE gap
  - orange: local kinetic model: top of kinetic continuum
  - red/green: global kinetic solution; as expected between the top pf the continuum and the middle of the TAE gap
- the local model (M4) cannot capture all the damping mechanisms: Landau and radiative are captured with analytical model; however not accurate in this case
- From this point forward, both runs with EPs and one without EPs will display the refined global solver (M2) results.

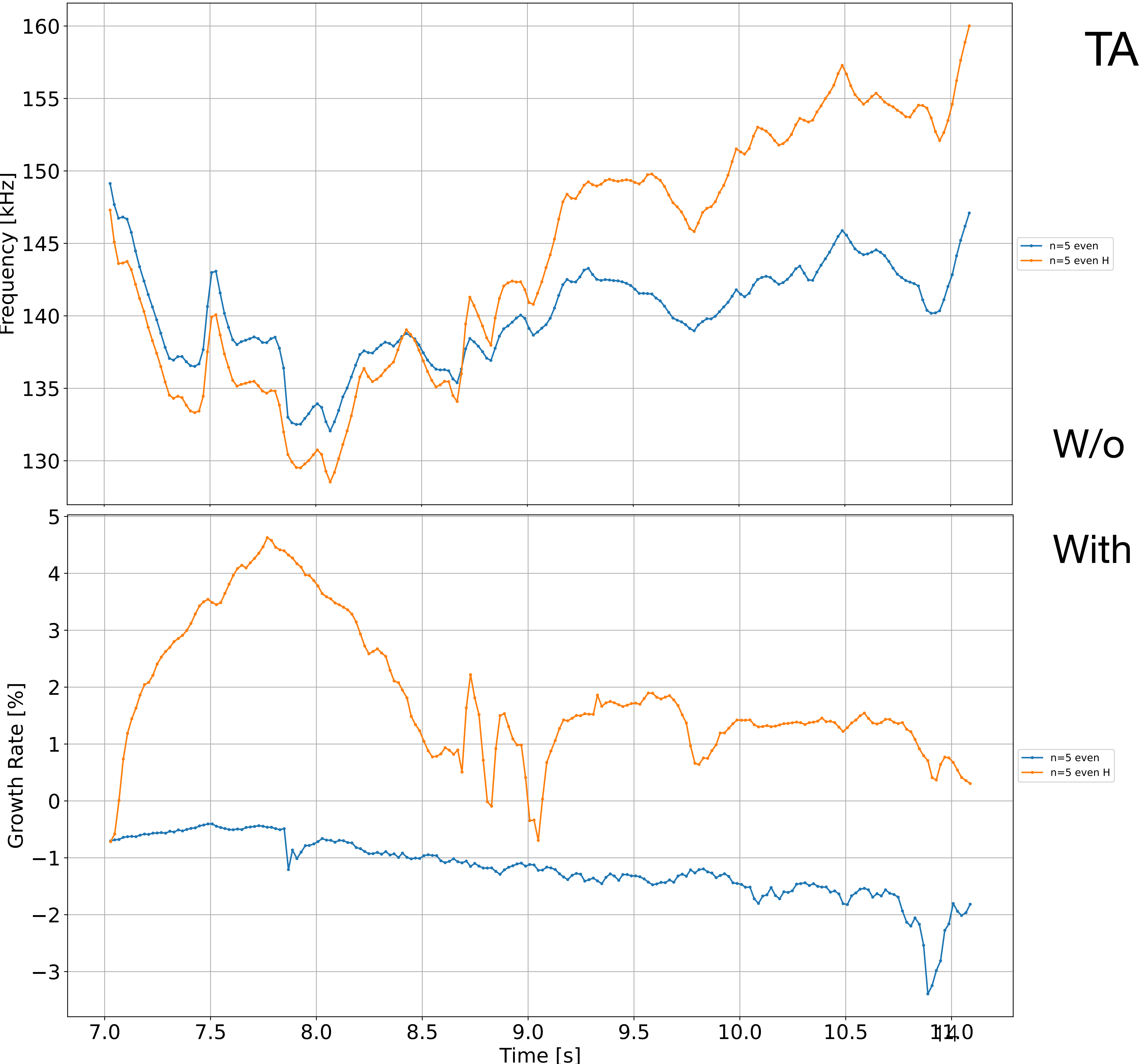
TAE frequency and growth-rate (D)



W/o D - blue

With D - orange

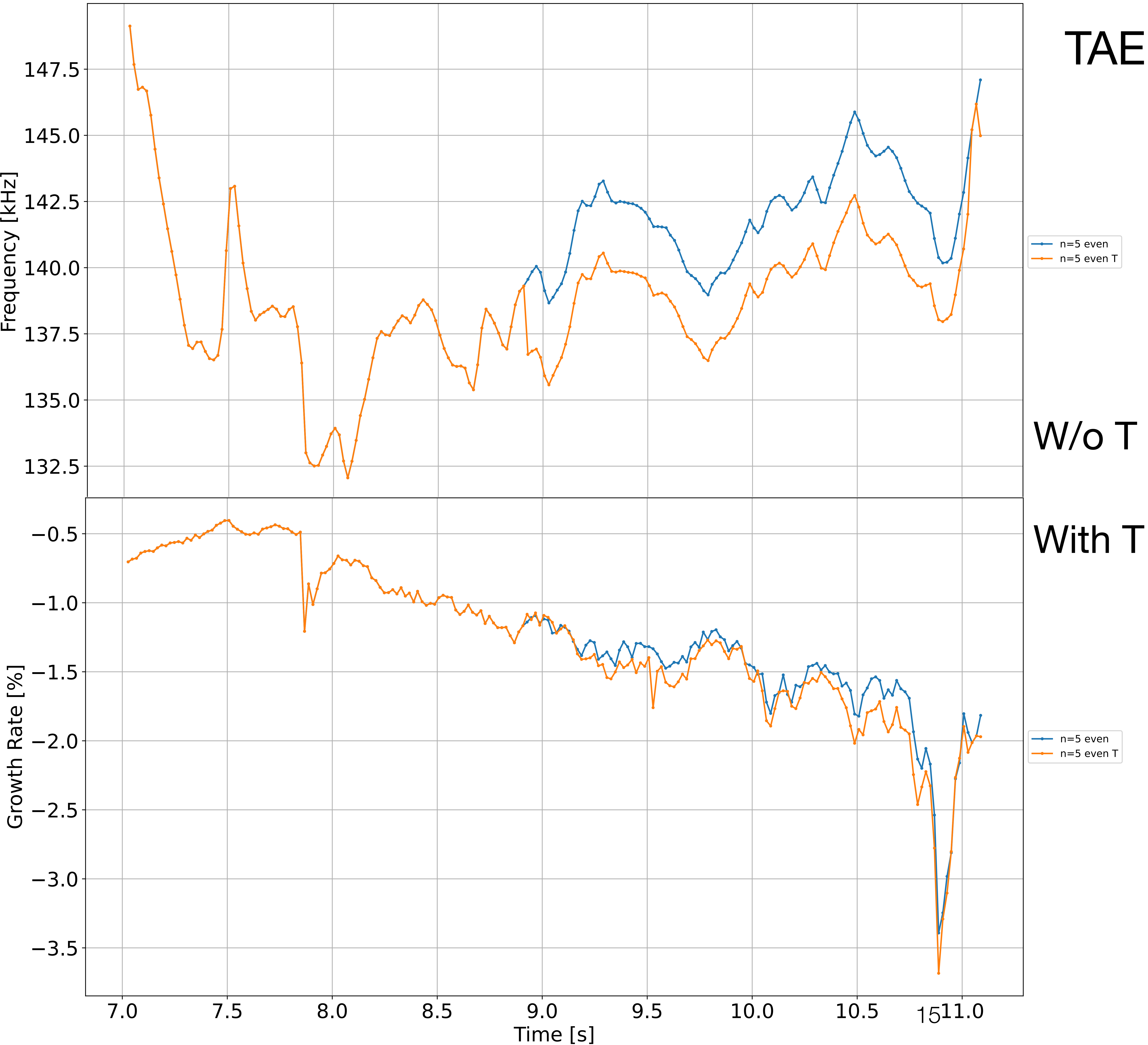
TAE frequency and growth-rate (H)



W/o H - blue

With H - orange

TAE frequency and growth-rate (T)



W/o T - blue

With T - orange

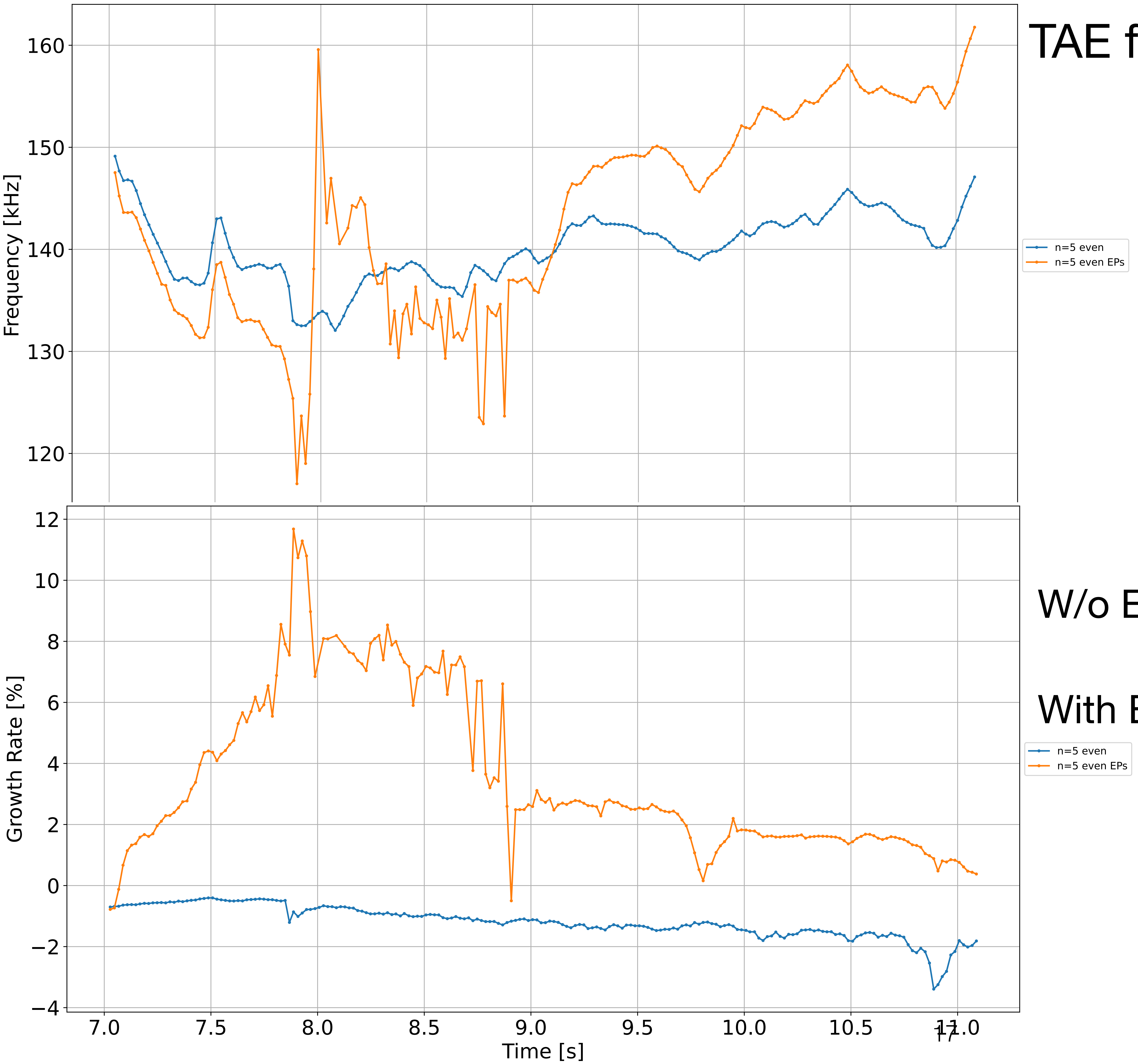
TAE frequency and growth-rate (alpha)

W/o alpha - blue

With alpha - orange

Very weak alpha drive

TAE frequency and growth-rate (all EPs)



- With H, D, T, and alphas turned on, we see a strong drive of the (n,m) = (5,5) even mode.
- The first 9s, Deuterium (NBI + ICRF) and Hydrogen (ICRF), were the main contributors to the drive.
- Once the D beam is switched off, the drive mainly comes from H.
- alphas and T do not contribute significantly to the drive
- For odd modes, we also notice drive but of lower magnitudes (~2.3%).

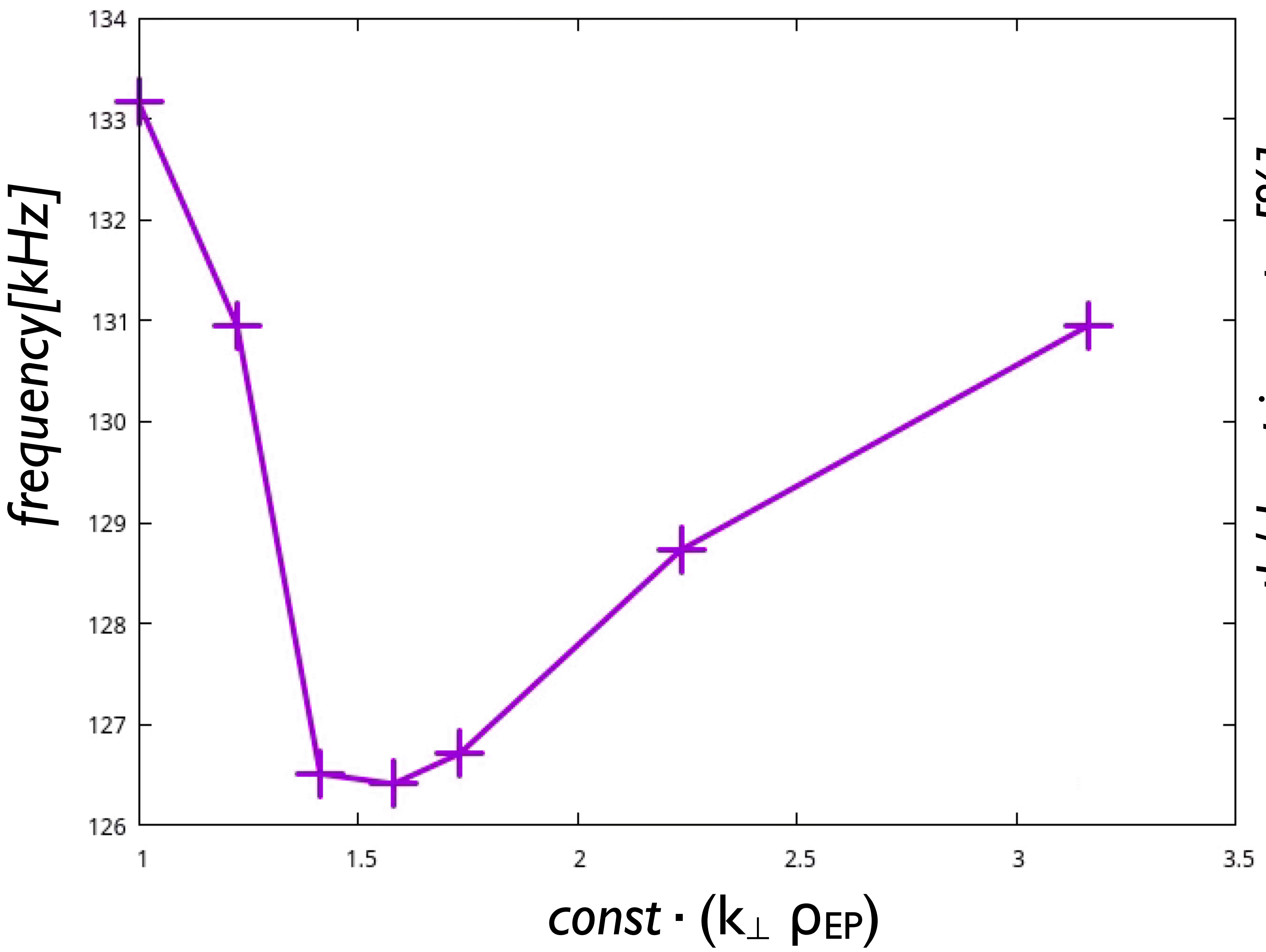
W/o EPs - blue

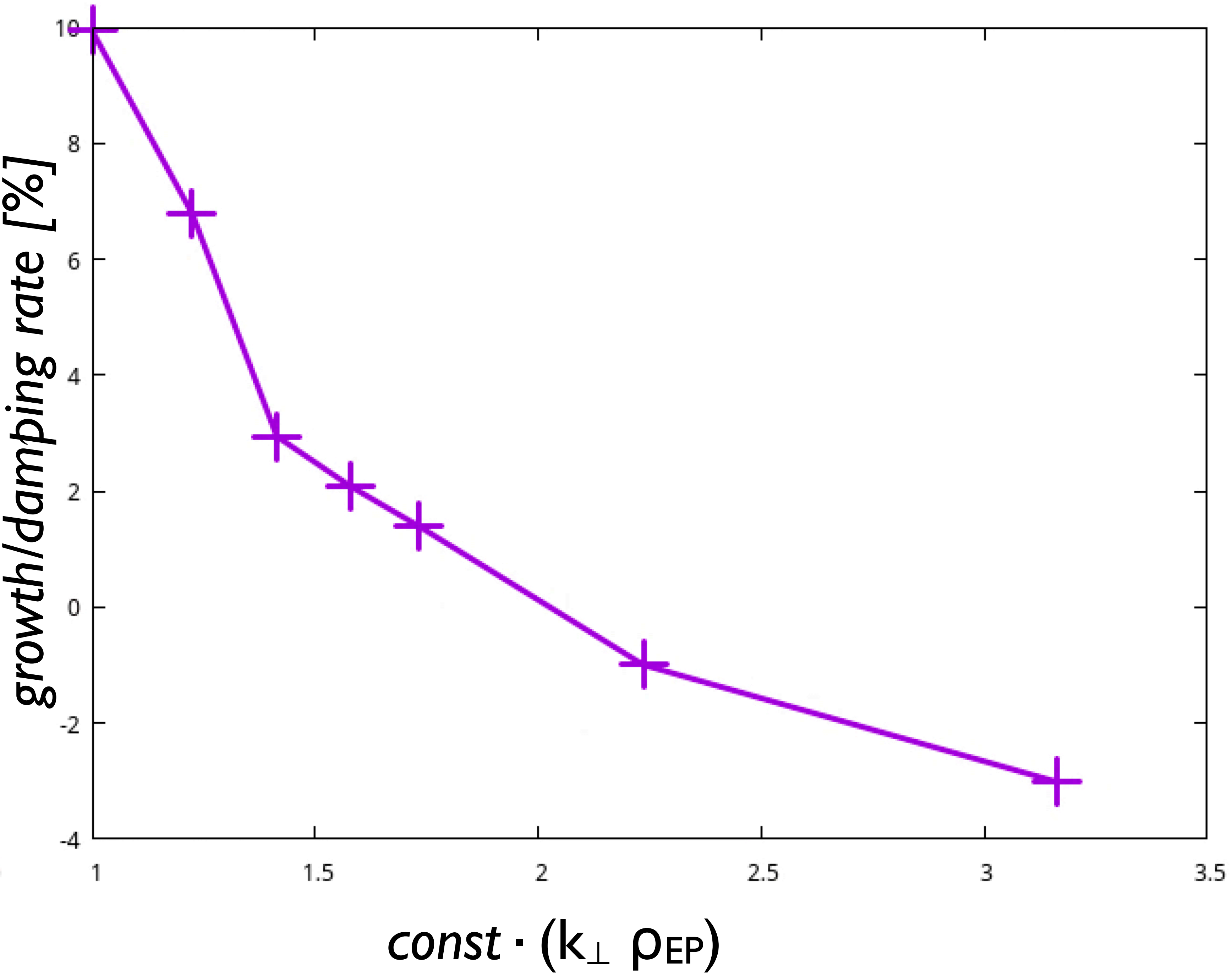
With EPs - orange

explanation of mismatch: scaling of frequency, drive and mode structure with FOW effects

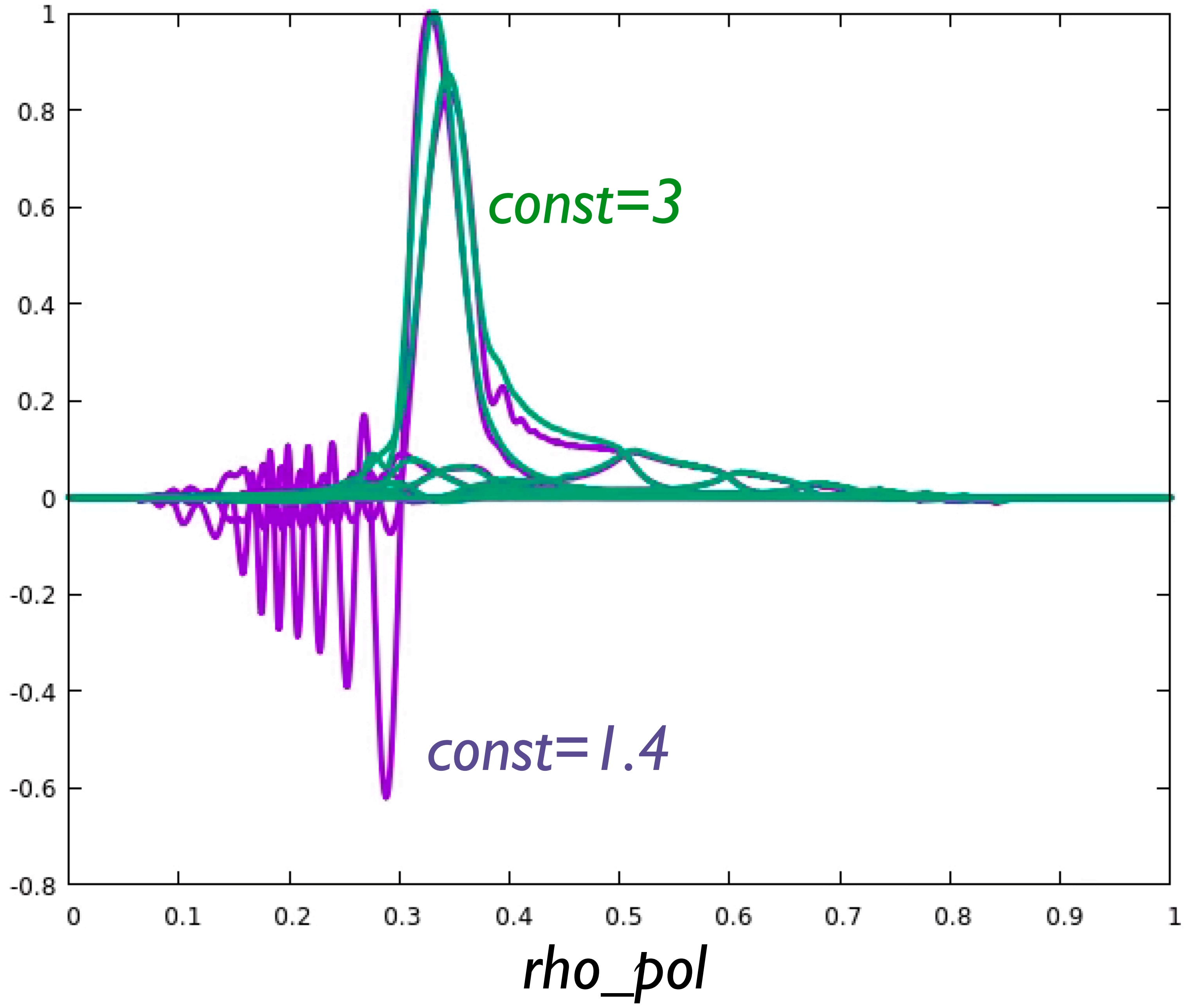
- fast WF version of LIGKA: use passing particles approximation for calculating kinetic response, also for FOW (finite orbit width) effects
- typically that is a good approximation for background particles and beam drive (passing particles, see AUG, ITER cases)
- for JET DT case, drive comes mainly from trapped H ions - differences are expected to be considerable: need for accurate distribution function
- here: check sensitivity of FOW effects by scaling $k_\perp \rho_{EP}$ in FOW terms

t = 7.98s



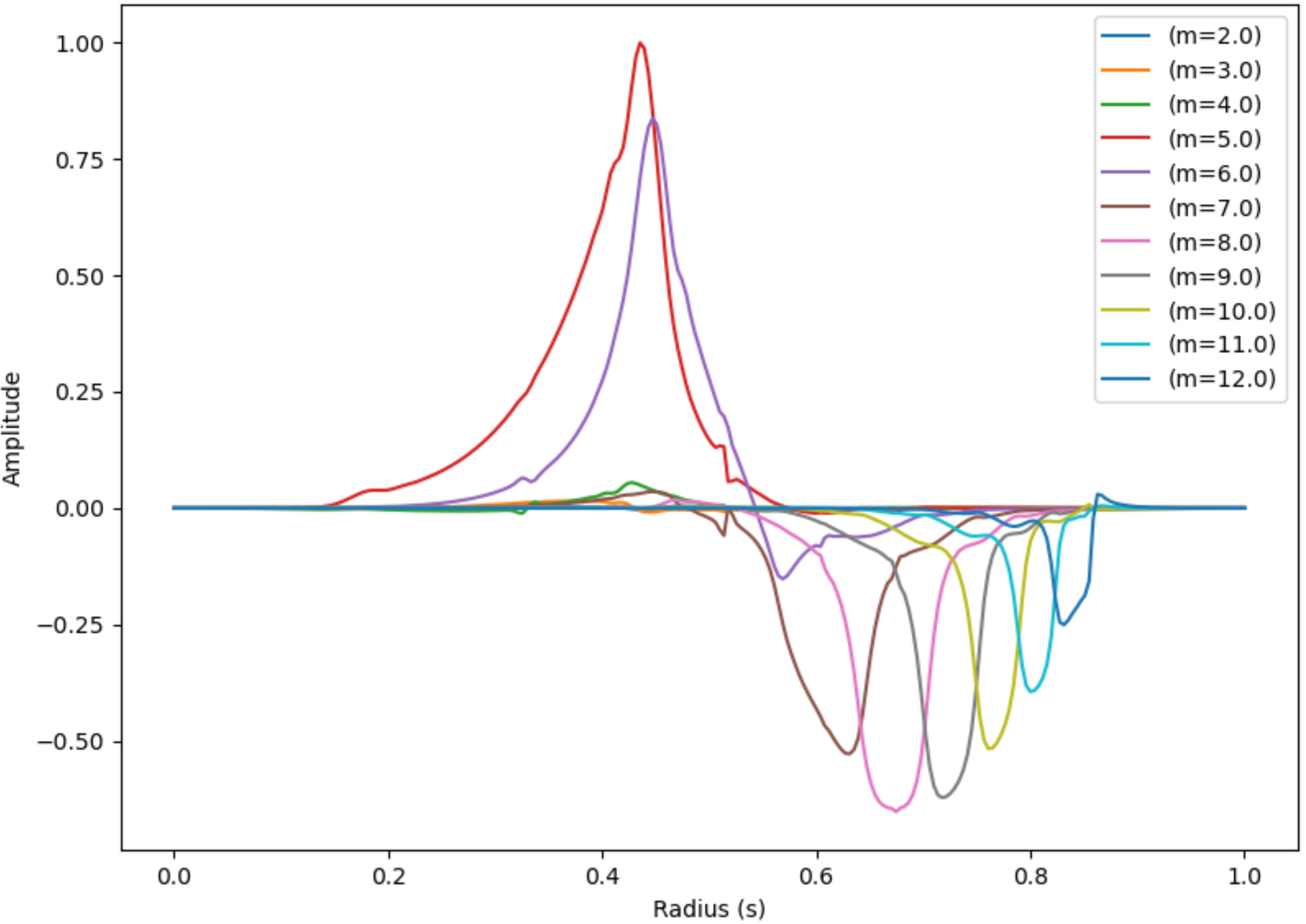


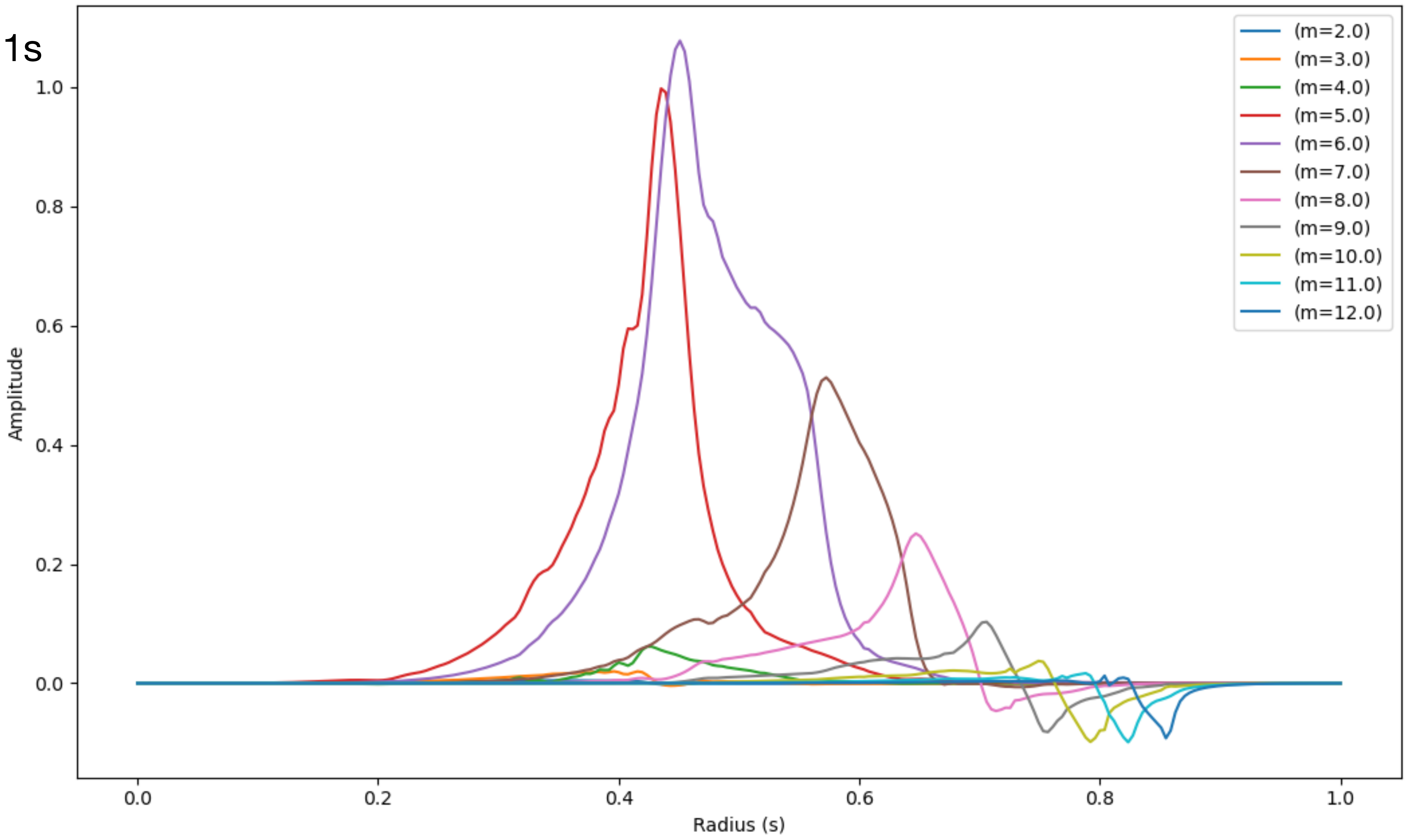
e.s. potential, n=5 even TAE



- result: high sensitivity to FOW effects; trapped H ions will have strong influence on all linear mode properties
- note: real frequency behaviour similar to ITPA FOW scan (first down, then up, as expected from theory)
- in addition: as shown in [Lauber, AAPPS-DPP 2021], trapped electrons in flat shear region damps KAW (not included fast WF version)

t = 9.1s

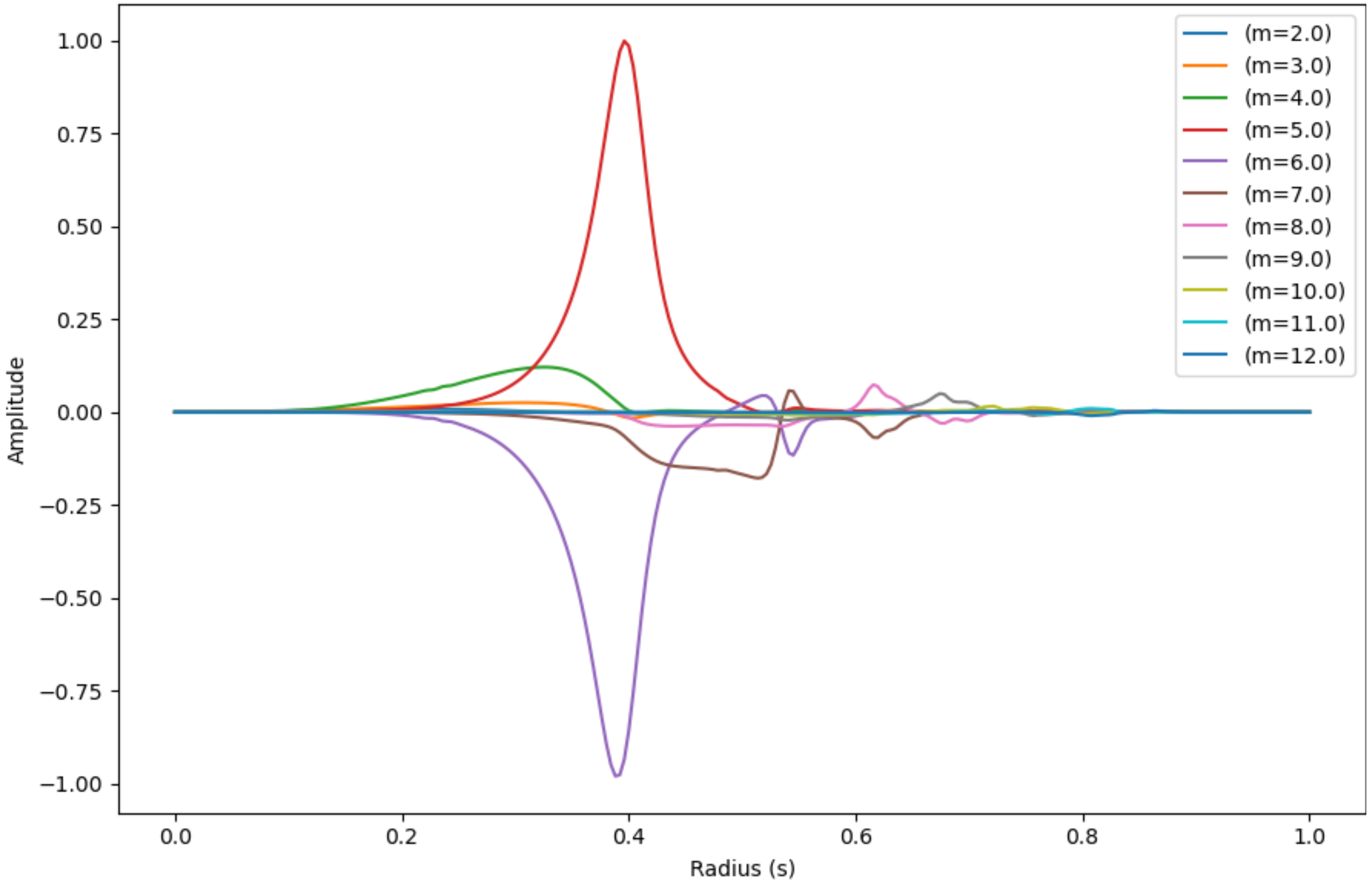


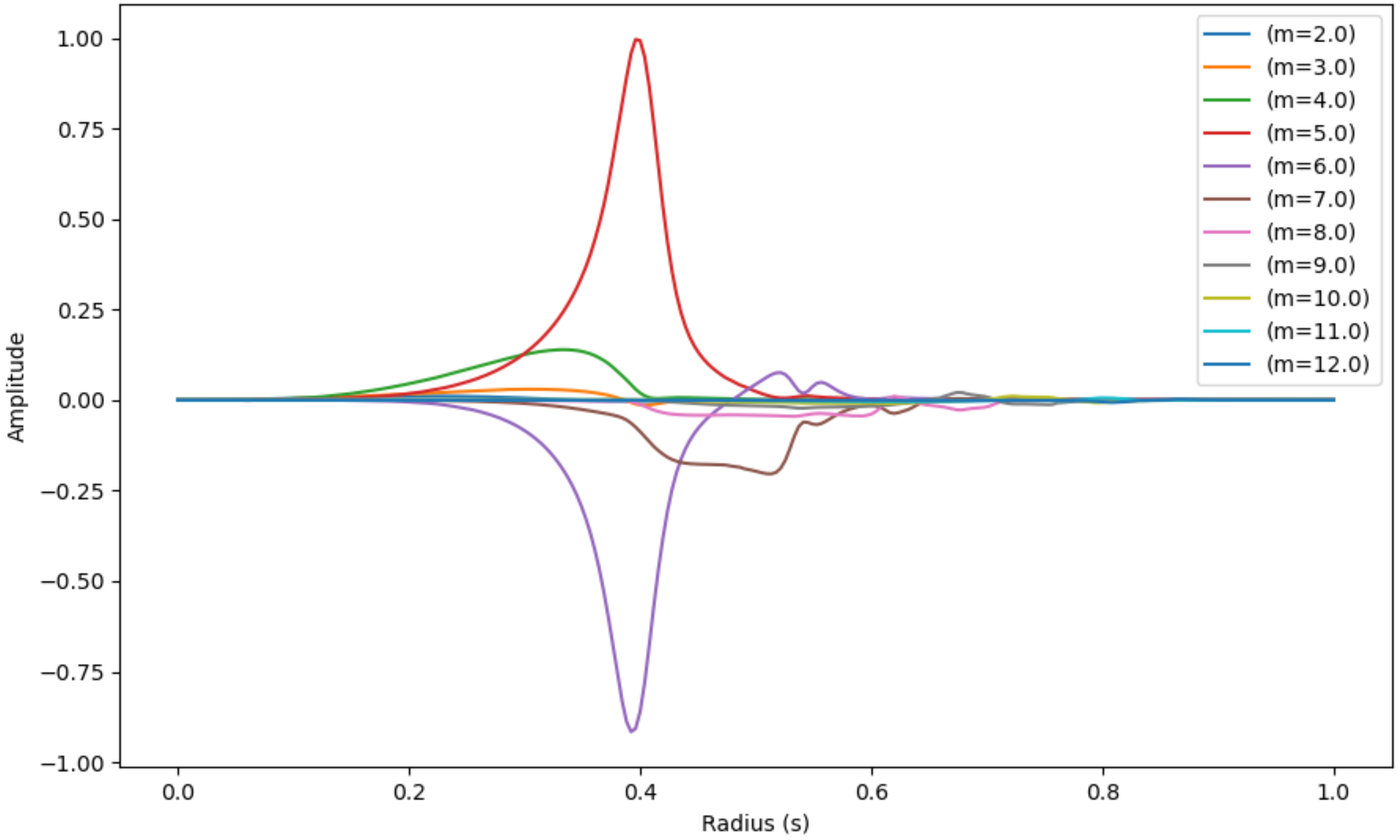


- n=5 even
- Position (r): 0.447
- Harmonics (m): [2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12.]
- Frequency: 140.472 kHz
- Growth rate: -1.177%

- n=5 even EPs
- Position (r): 0.447
- Harmonics (m): [2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12.]
- Frequency: 139.834 kHz
- Growth rate: 2.473%.

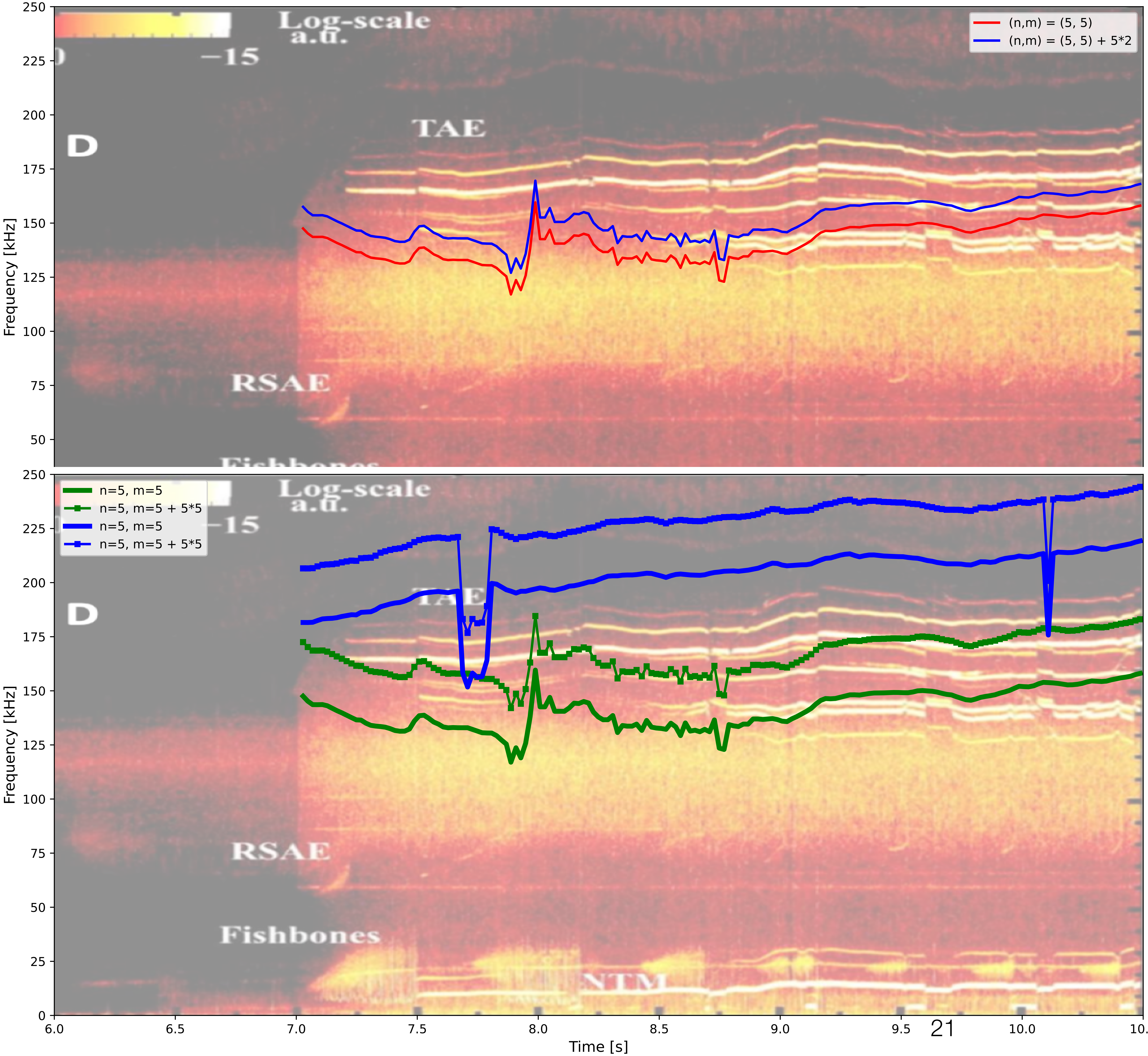
t = 8.508s



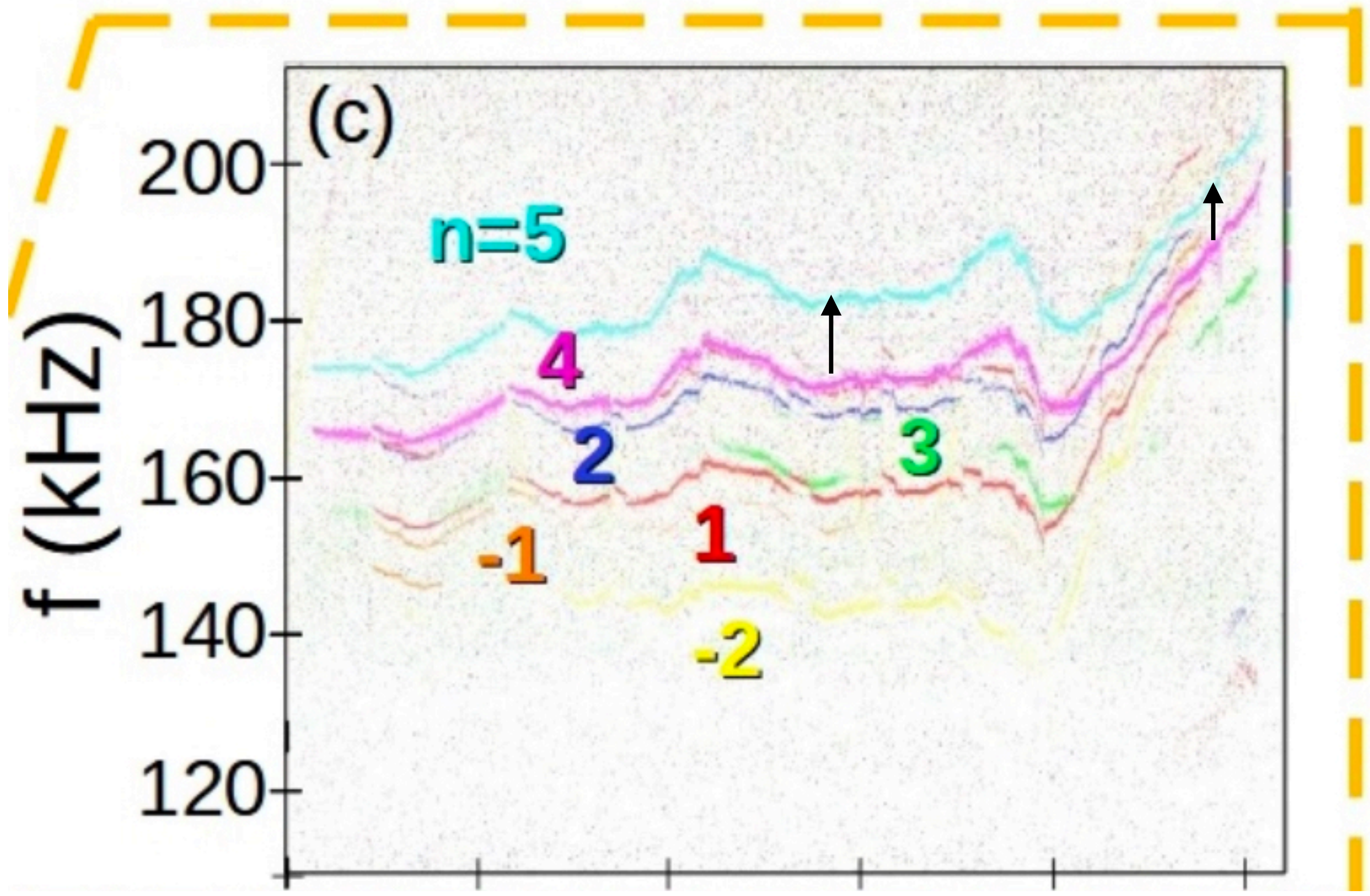


- n=5 odd
- Position (r): 0.399
- Harmonics (m): [2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12.]
- Frequency: 196.337 kHz
- Growth rate: -1.373%

- n=5 odd EPs
- Position (r): 0.399
- Harmonics (m): [2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12.]
- Frequency: 203.072 kHz
- Growth rate: 2.360%.



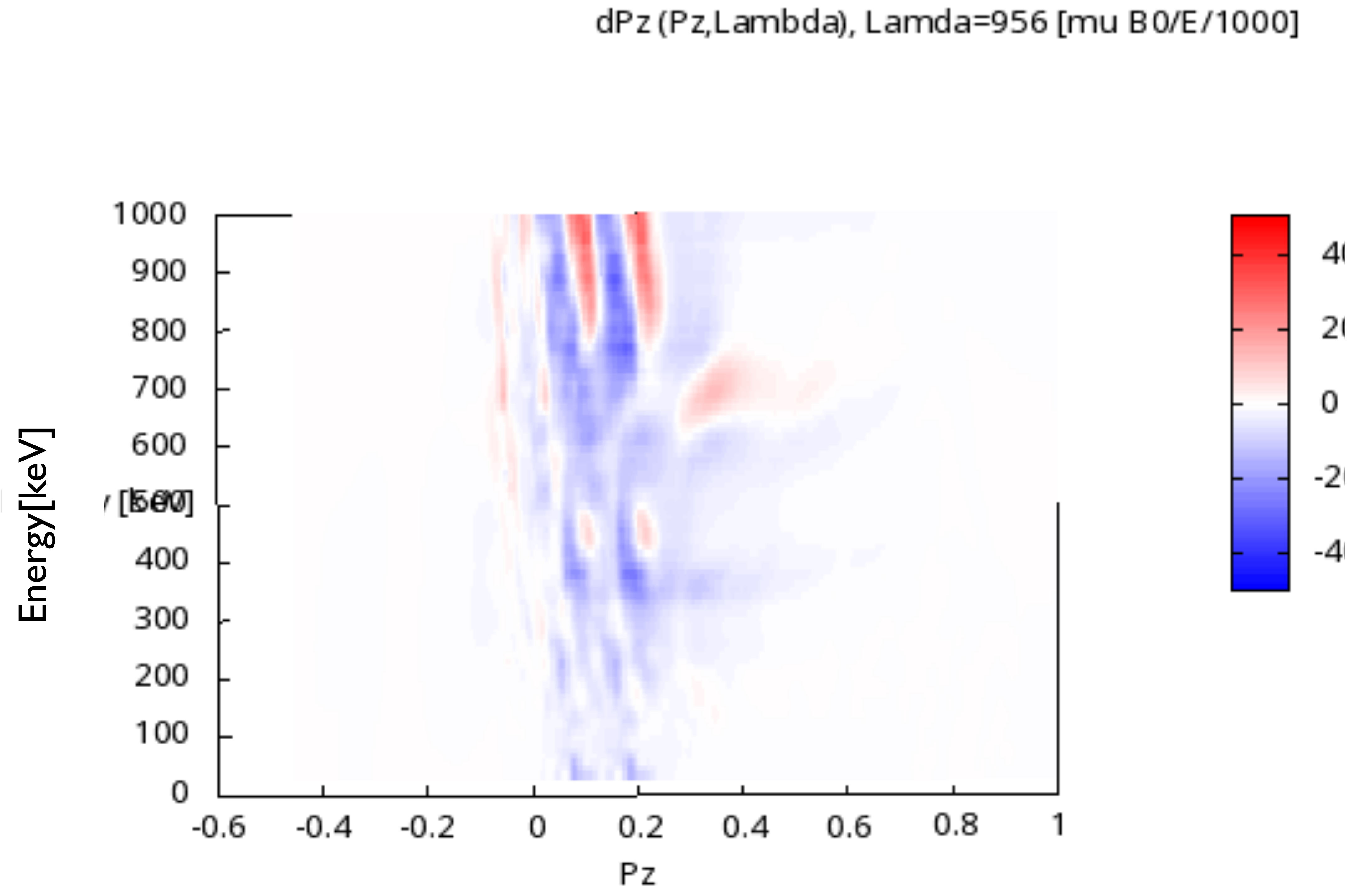
- With a rotation of 2 kHz, which means for n=5, adding 10 kHz to the frequency.
- While the trend is being followed, as expected, the frequency of both even and odd nodes no not reproduce the experiment
- Looking at the magnetic data and the difference between n=4 and n=5, a rotation of 5 kHz was assumed.
- Applying the rotation to both odd and even (5,5) modes, similar frequencies are found



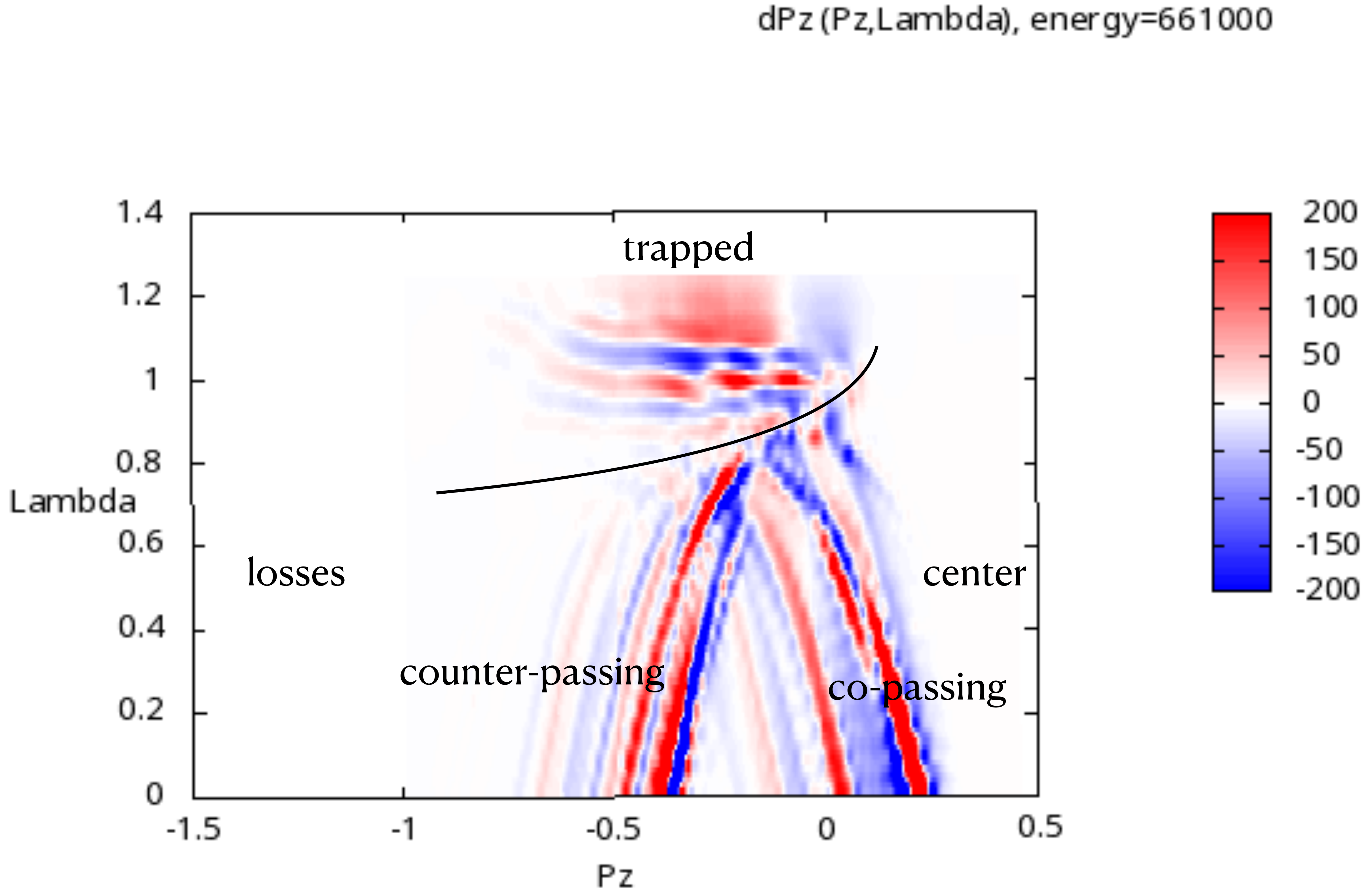
EP transport: calculate EP fluxes for n=4+5 modes: H ions (ATEP)

t = 8.508s

dPz/dt for barely trapped hydrogen ions, Λ≈1
fixed mode amplitude: $dB/B= 10^{-3}$



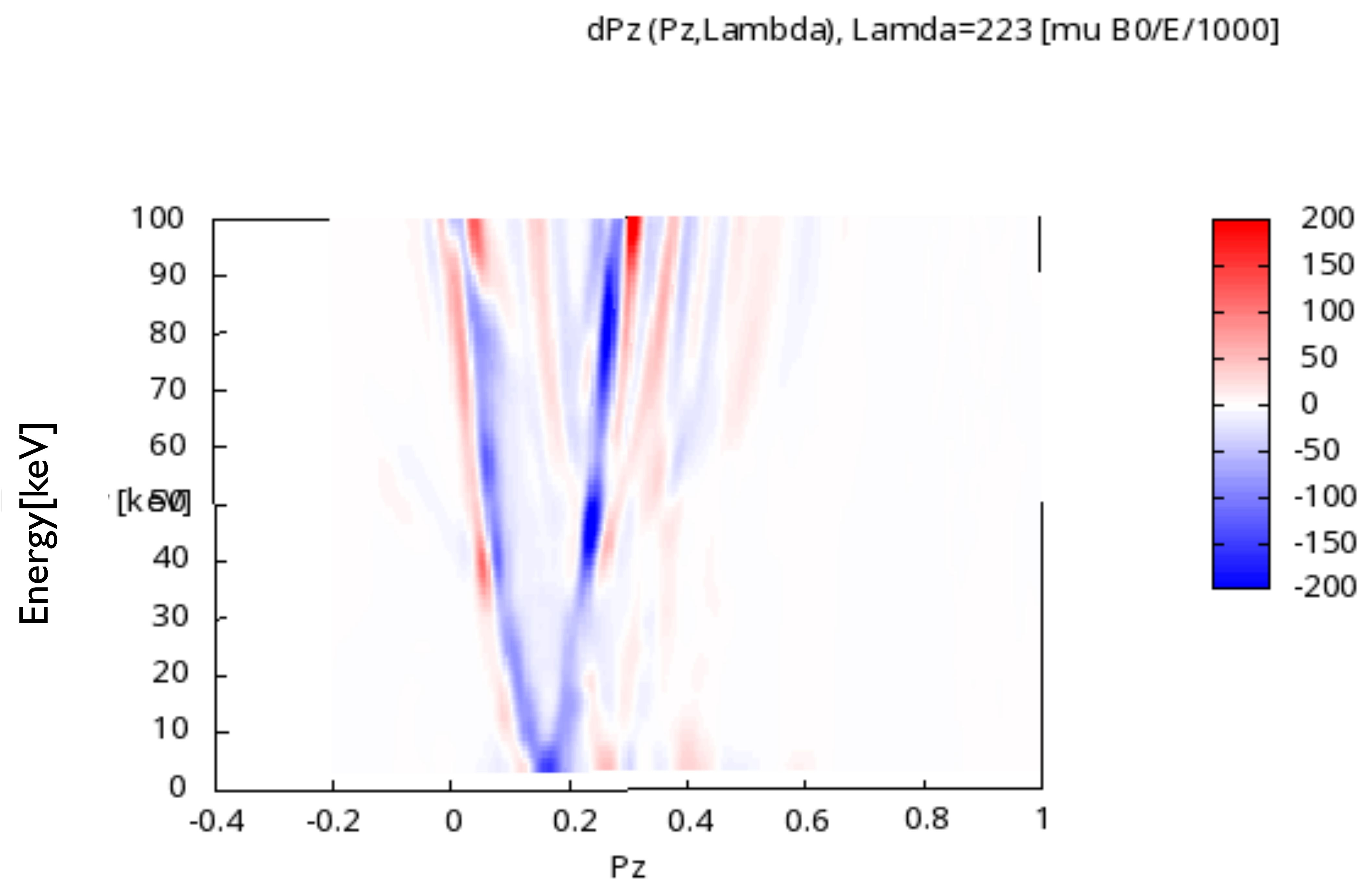
dPz/dt for 660 keV H ions



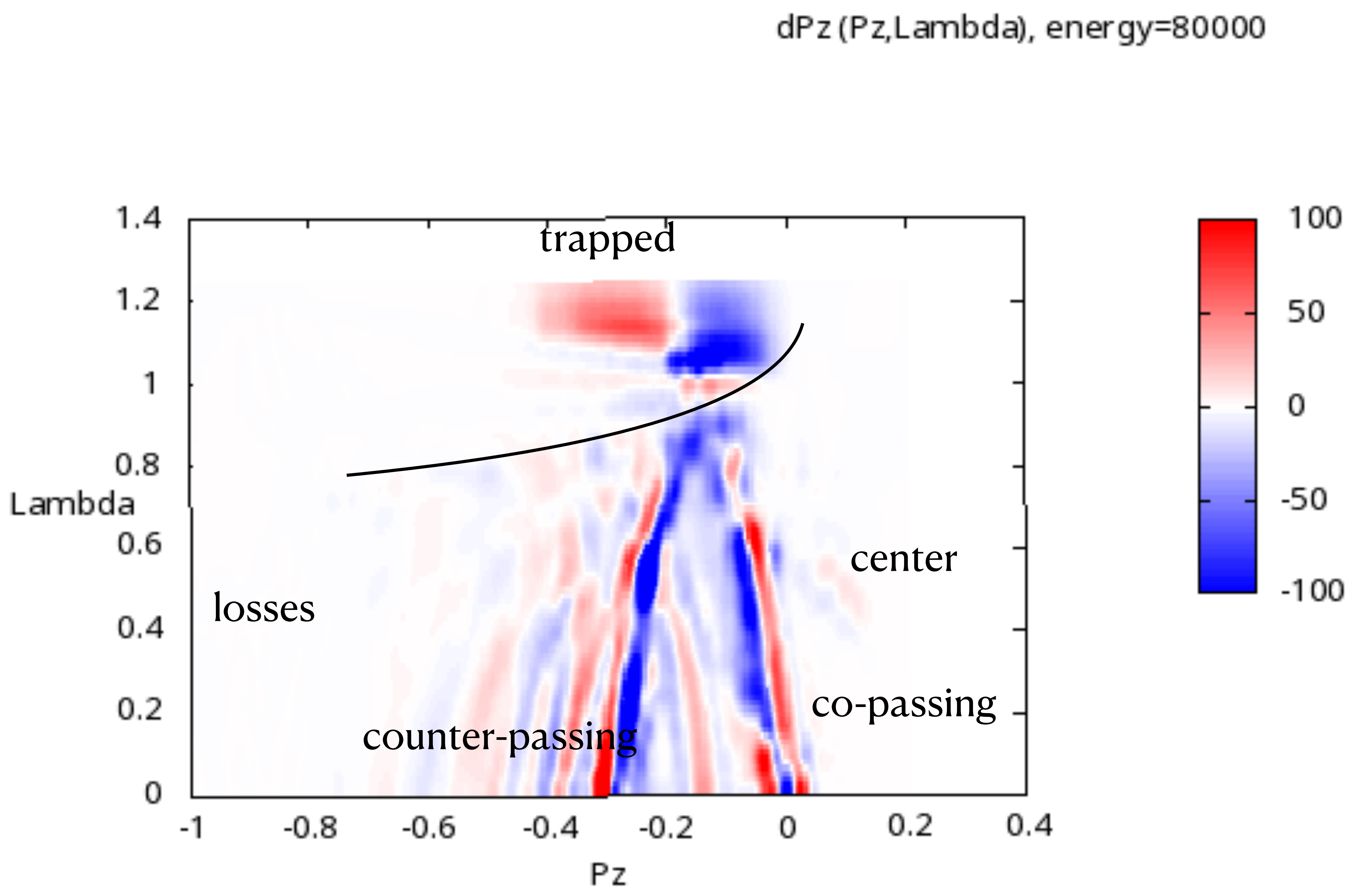
F_{EP}(Pz,E, Λ) needed to calculate EP relaxation

EP transport: calculate EP fluxes for n=4+5 modes: D ions (ATEP)

dPz/dt for deeply passing ions, Λ≈0.2
fixed mode amplitude: dB/B= 10^{-3}



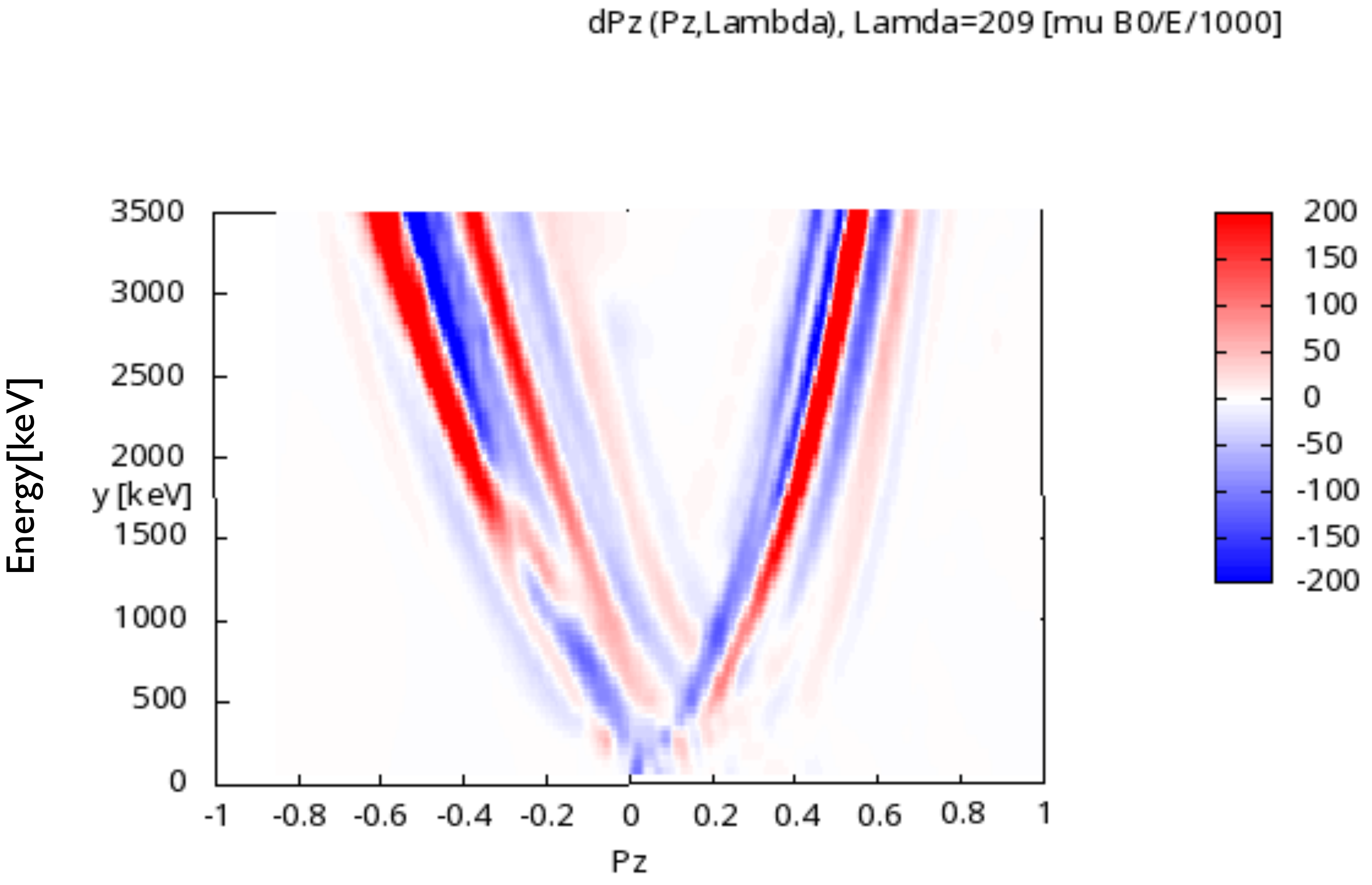
dPz/dt for 80keV beam D ions



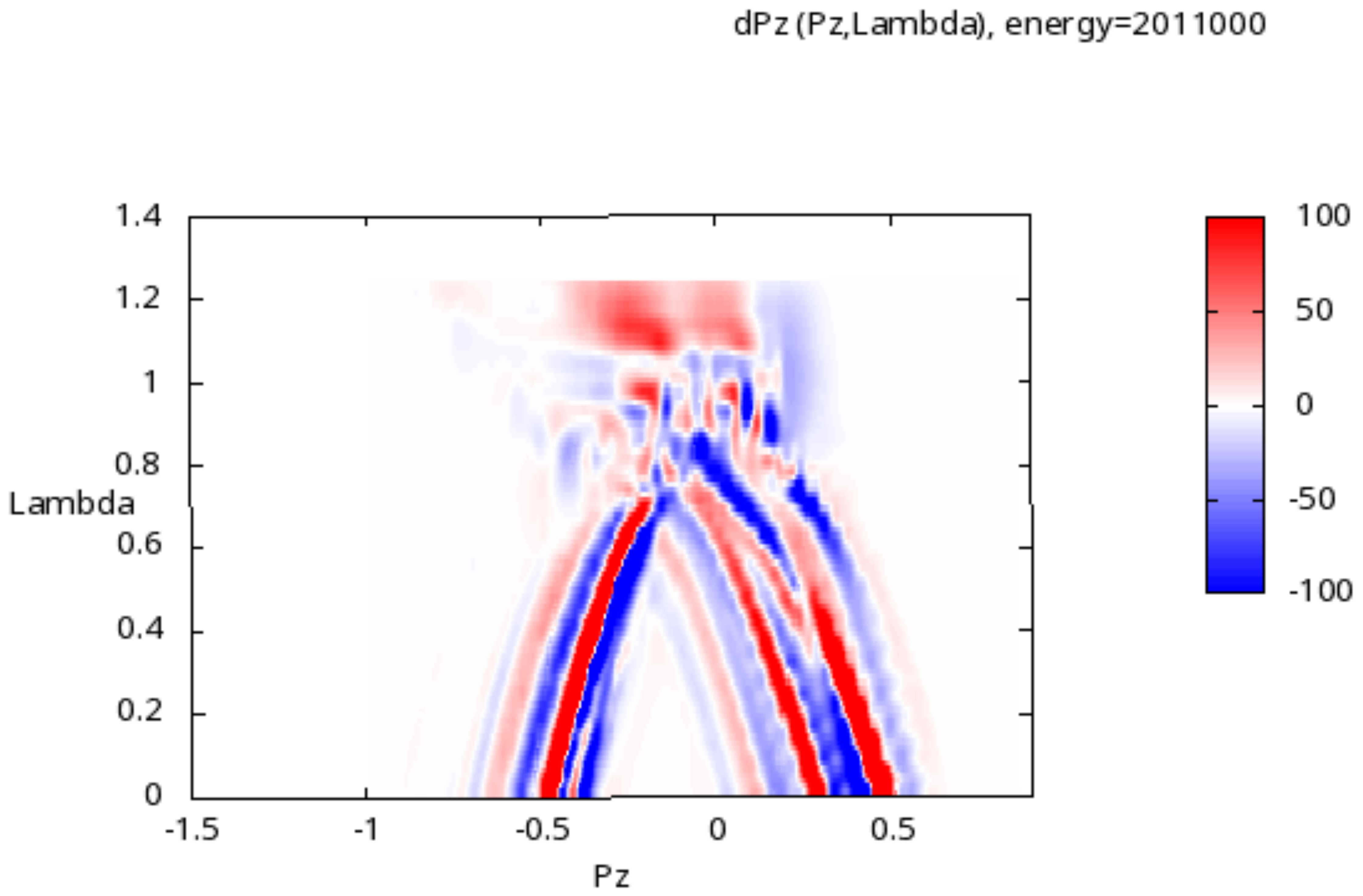
$F_{EP}(Pz, E, \Lambda)$ needed to calculate EP relaxation

EP transport: calculate EP fluxes for n=4+5 modes: alpha particles (ATEP)

dPz/dt for deeply passing alphas , Λ≈0.2
fixed mode amplitude: dB/B= 10^{-3}



dPz/dt for 2MeV alphas



Overview - Outlook

- Objectives:
    - perform time-dependent linear analysis on experimental DT data using IMAS-integrated EP-Stability-WF
    - tune fast models to give accurate results (1-week runtime for everything/ so far no parallelisation in ‚time‘ done: further reduction of runtime can be easily obtained)
    - get valuable insights into the results but also the potential problems
    - identify with certainty effects that need to be studied (linear vs non-linear) - not yet
- improvements needed for more accurate modelling:
    - No NBI distributions are present in the IDS (using Maxwellian)
    - q=1 surface not properly captured during Sawtooth cycles
    - fast pressure perpendicular component (H)
    - missing rotation profile
    - experimental estimates of saturated amplitudes (at least relative estimates)
- Outlook:
    - Repeat when distributions become available - differences due to FOW effects expected
    - Run ATEP for EP transport and profile relaxation