Gyrokinetic study of co-existing Alfvén eigenmode and microturbulence in KSTAR

G.J. Choi[1], S.J. Park[1], T.S. Hahm[1], Y.-S. Na[1],
J. Kang[2], J. Kim[2], J.M. Kwon[2], T. Rhee[2] and KSTAR Team[2],
P. Liu[3], X.S. Wei[3], Z. Lin[3] and GTC Team[3]

[1] Seoul National University
[2] Korea Institute of Fusion Energy
[3] University of California, Irvine

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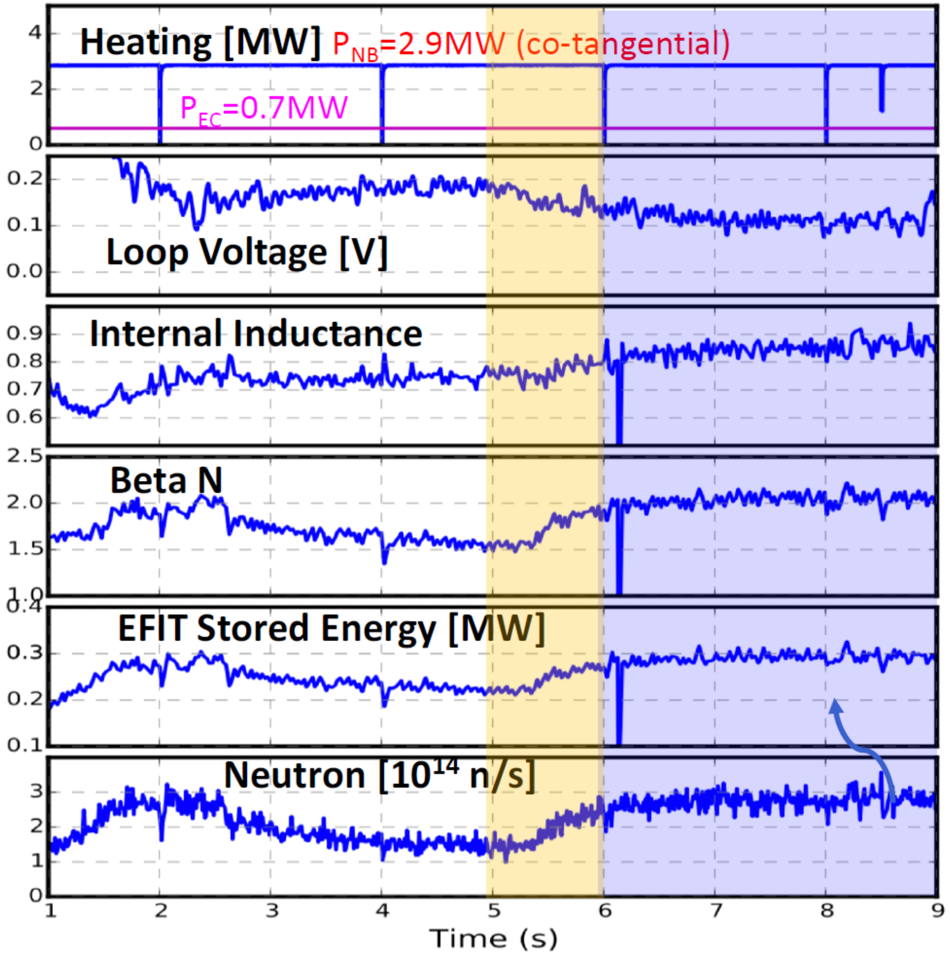
AE control by ECCD in KSTAR

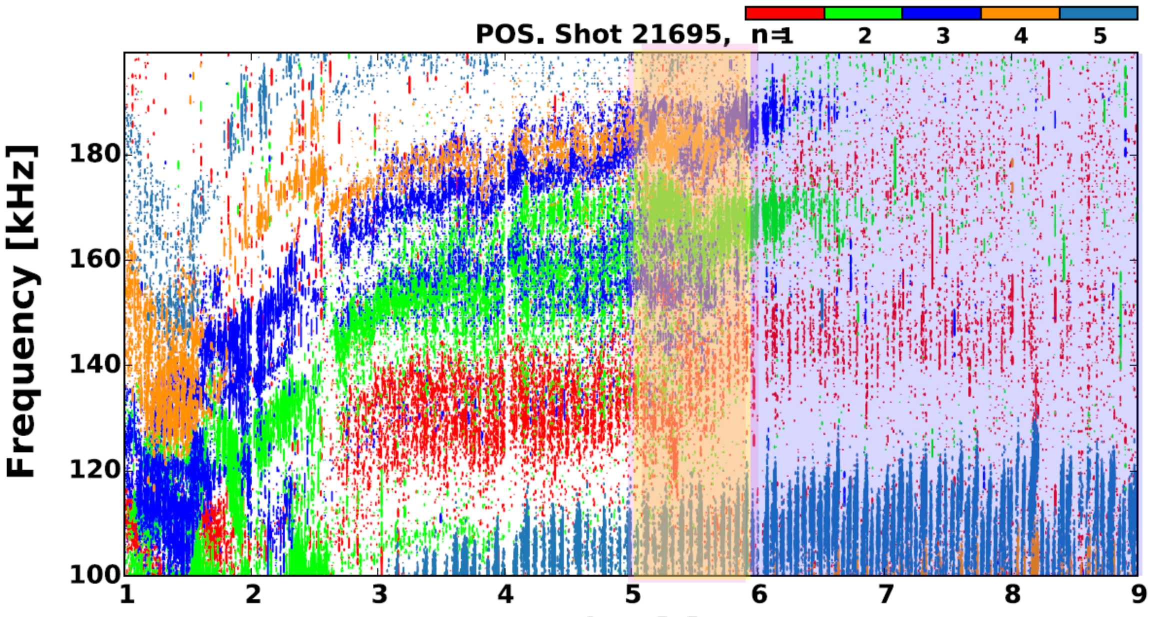
Only one Control Knob | **Z_{EC} scan: +30cm → +15cm (5.0s – 5.5s)**

Performance enhancement during the ECCD scan

J. Kim *et al.*, NF **62**, 026029 (2022)



Mirnov Coil Spectogram



AE-active

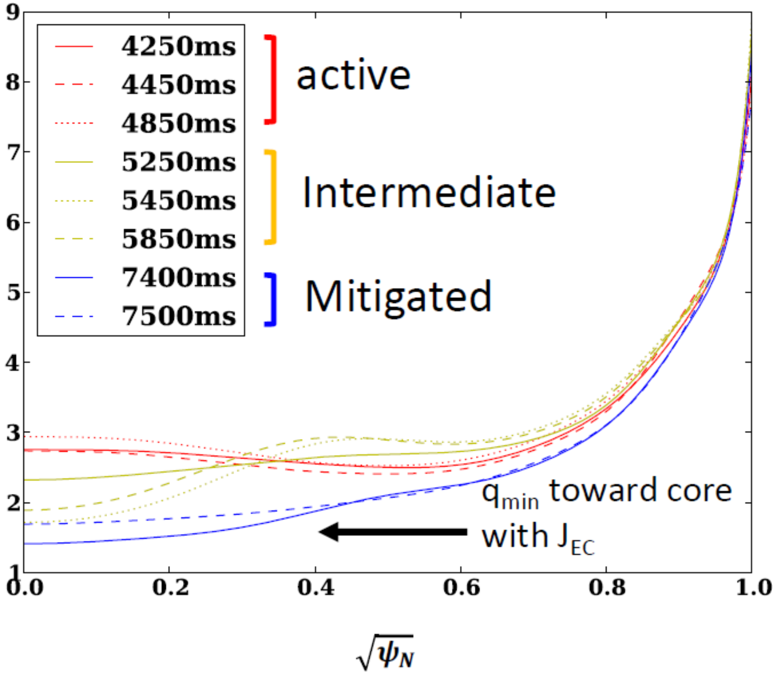
Intermediate Change in AEs

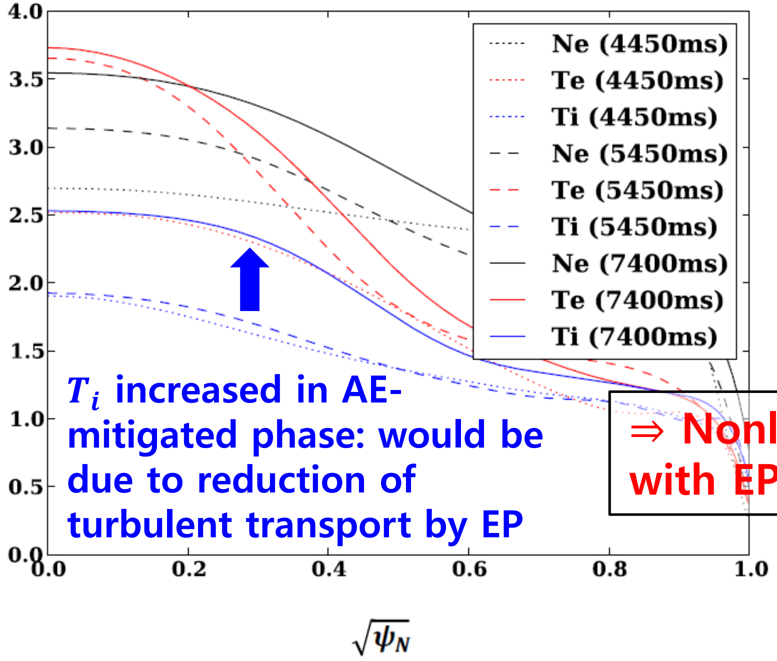
AE mitigation

Multi toroidal mode number could be existed

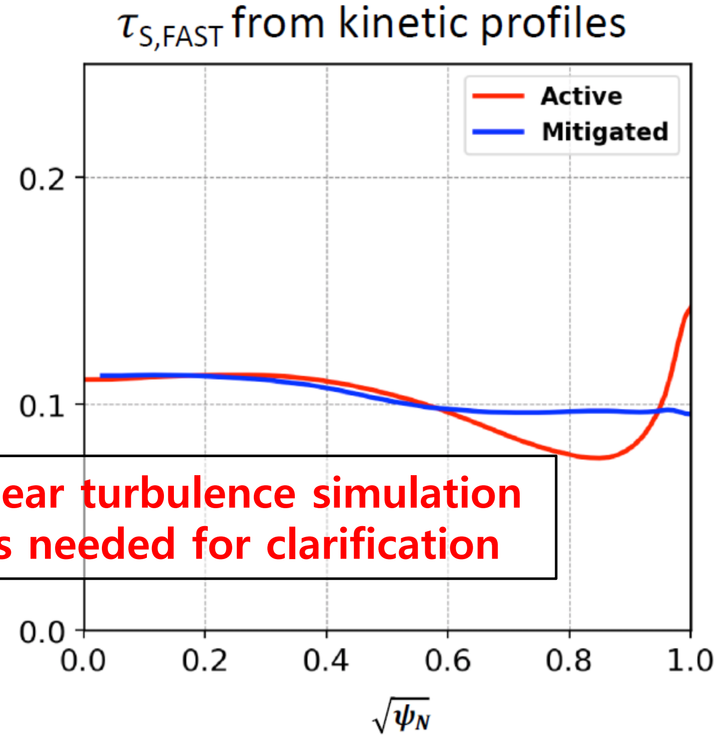
- Decrease of loop voltage (-200 mV → -110 mV) while the AE is mitigated. → Increased non-inductive current fraction (NBCD or Bootstrap ↑)
- AE mitigation while applying the ECCD to the proper location → Enhanced fast-ion confinement (mainly co-passing by co-tangential NBI) → Increase of NBCD efficiency → Overall performance increases.

Enhanced KSTAR performance by AE mitigation


Safety Factor


Kinetic profiles [n_e - 10^{19} #m^{-3} , T_e/T_i – keV]

T_i increased in AE-mitigated phase: would be due to reduction of turbulent transport by EP


$\tau_{S,FAST}$ from kinetic profiles

⇒ Nonlinear turbulence simulation with EP is needed for clarification

- Kinetic equilibrium reconstruction shows q profile evolution of each phase.
  Almost consistent for stable region and dynamic for evolution phase.
  (>0.5 is TRANSP constrained and other region is MSE constrained)
- Increment of core kinetic profile is also observed.
- Classical fast ion slowing down time is almost consistent among active/mitigated phase.
  → Mode is responsible for fast ion transport.

Complex EP-plasma interactions

- Nonlinear behavior of EP is extremely complex, as it interacts with plasma by mesoscale AEs and microturbulence in various channels (multi-scale problem).
  - EP ↔ AE: EP loss and redistribution by wave-particle interaction with AE [1]
  - EP ↔ turbulence: turbulence stability change by EP [2] vs turbulent transport of EP [3]
  - AE ↔ turbulence: turbulence regulation of AE-induced EP transport [4]
    or AE suppresses turbulent plasma transport [5]
  - AE ↔ plasma: collisionless heating accompanied to wave-wave interaction of AEs [6,7]
  - Turbulence ↔ plasma: turbulence drive by ∇n, ∇T vs turbulent transport
  - EP ↔ plasma: collisional energy exchange

- For a comprehensive study of these complex EP-plasma interactions in magnetized fusion plasmas, we need first-principles **gyrokinetic** simulations which can contain all kinetic effects and non-perturbative EP effects for phenomena slower than ion gyrofrequency.
  ⇒ Our goal: nonlinear gyrokinetic simulations of KSTAR plasmas considering EP, AEs and turbulence altogether.

[1] R.B. White *et al.*, PF **26**, 2958 (1983)
[2] A. Di Siena *et al.*, NF **58**, 054002 (2018)
[3] C. Angioni and A.G. Peeters, PoP **15**, 052307 (2008)
[4] P. Liu *et al.*, PRL **128**, in press (2022)
[5] S. Mazzi, PhD Thesis (2022)
[6] T.S. Hahm and L. Chen, PRL **74**, 266 (1995)
[7] Z. Qiu *et al.*, PRL **120**, 135001 (2018)

Well-established GTC capability of AE study

- GTC: Global gyrokinetic code for multiple nonlinear kinetic-MHD processes
- **TAE**: analytic [1], DIII-D [2,3], KSTAR [4], HL-2A [5], JET [6]
- **RSAE**: DIII-D [7,8], DIII-D nonlinear [9]
- **BAE**: analytic nonlinear [10-12], model e-BAE [13], HL-2A [14]
- **BAAE**: analytic [15], analytic nonlinear [16]
- **EPM**: analytic [17]
- **EGAM**: analytic [18]
- **LF(A)M**: DIII-D [19,20]
- **BTG**: JET [21]
- **Inter-codes validation & verification**:
  RSAE (analytic) [22], BAE (analytic) [23], RSAE/TAE (DIII-D) [24], RSAE (DIII-D) [25], Kink (DIII-D) [26]

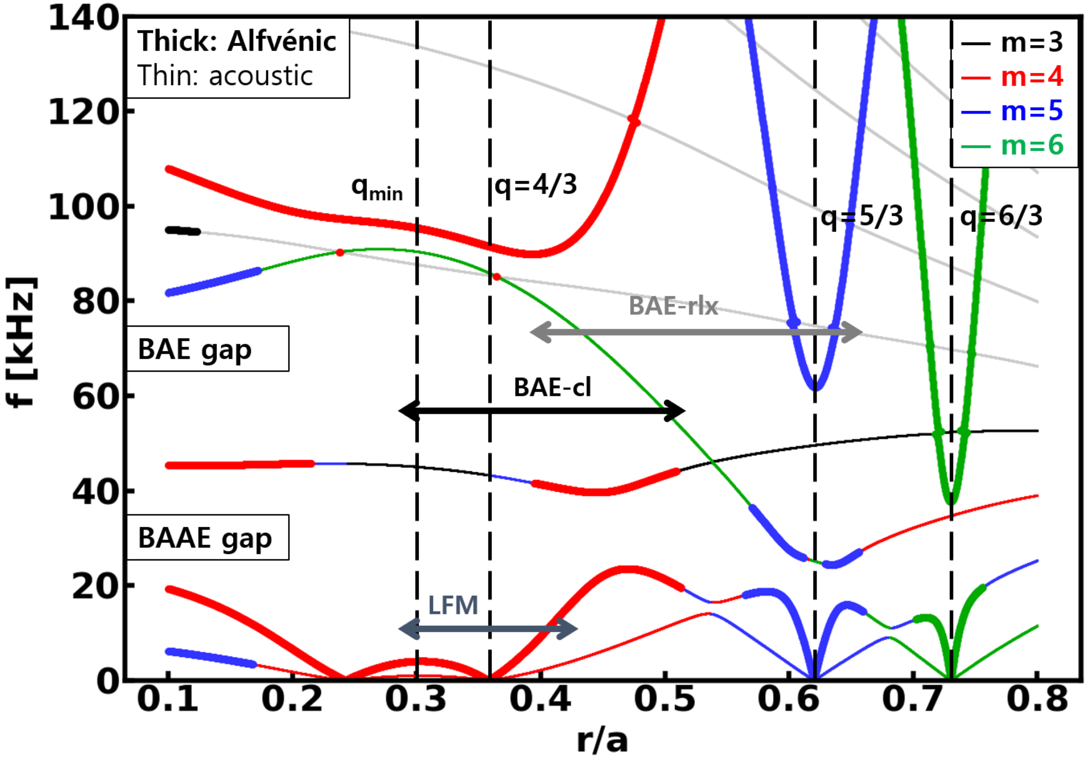
[1] W.L. Zhang *et al.*, PoP **19**, 022507 (2012)
[2] Z.X. Wang *et al.*, PRL **111**, 145003 (2013)
[3] Z.X. Wang *et al.*, PoP **22**, 022509 (2015)
[4] H. Rizvi, C. M. Ryu, and Z. Lin, NF **56**, 112016 (2016)
[5] H. He *et al.*, NF **58**, 126023 (2018)
[6] V. Aslanyan *et al.*, NF **59**, 026008 (2019)
[7] W. Deng *et al.*, NF **52**, 043006 (2012)
[8] H.Y. Wang *et al.*, PST **23**, 015101 (2021)
[9] P. Liu *et al.*, PRL **128**, in press (2022)
[10] H.S. Zhang, Z. Lin and I. Holod., PoP **17**, 112505 (2010)
[11] H.S. Zhang *et al.*, PoP **20**, 012510 (2013)
[12] H.S. Zhang and Z. Lin, PST **15**, 969 (2013)
[13] J.Y. Cheng *et al.*, PoP **23**, 052504 (2016)
[14] Y. Chen *et al.*, PoP **26**, 102507 (2019)
[15] Y. Liu *et al.*, NF **57**, 114001 (2017)
[16] J.Y. Cheng *et al.*, PoP **24**, 092516 (2017)
[17] C.X. Zhang *et al.*, PoP **20**, 052501 (2013)
[18] Y. Chen *et al.*, CPL **37**, 095201 (2020)
[19] G.J. Choi *et al.*, NF **61**, 066007 (2021)
[20] W.W. Heidbrink *et al.*, NF **61**, 106021 (2021)
[21] N. Fil *et al.*, PoP **28**, 102511 (2021)
[22] W. Deng *et al.*, PoP **17**, 112504 (2010)
[23] H.S. Zhang *et al.*, PoP **17**, 112505 (2010)
[24] D.A. Spong *et al.*, PoP **19**, 082511 (2012)
[25] S. Taimourzadeh *et al.*, NF **59**, 066006 (2019)
[26] G. Brochard *et al.*, NF **62**, 036021 (2022)

Linear GTC finds both BAE and LFM in DIII-D

[W.W. Heidbrink *et al.,* NF **61**, 016029 (2021)]

- “BAAE” activity persists after turning-off NBI in DIII-D discharges including #178631: “LFM”.
- In #178631, GTC finds unstable $n = 3$ BAE with both classical and relaxed fast ion profiles.
- **Without fast ions**, GTC finds unstable LFM inside BAAE gap.
- Electrostatic simulation shows no growing n=3 mode. ⇒ not an electrostatic mode.
- Large $\gamma/\omega \sim 1$ for LFM
  ⇒ strong perpendicular non-resonant drive
  from energy exchange analysis.
- Only modest change by parallel current ⇒
  LFM: thermal pressure-driven Alfvenic mode.
  [G.J. Choi *et al.,* NF **61**, 066007 (2021)]
- Consistent with “**LFAM**” from analytic theory.
  [W.W. Heidbrink *et al.,* NF **61**, 016029 (2021)]

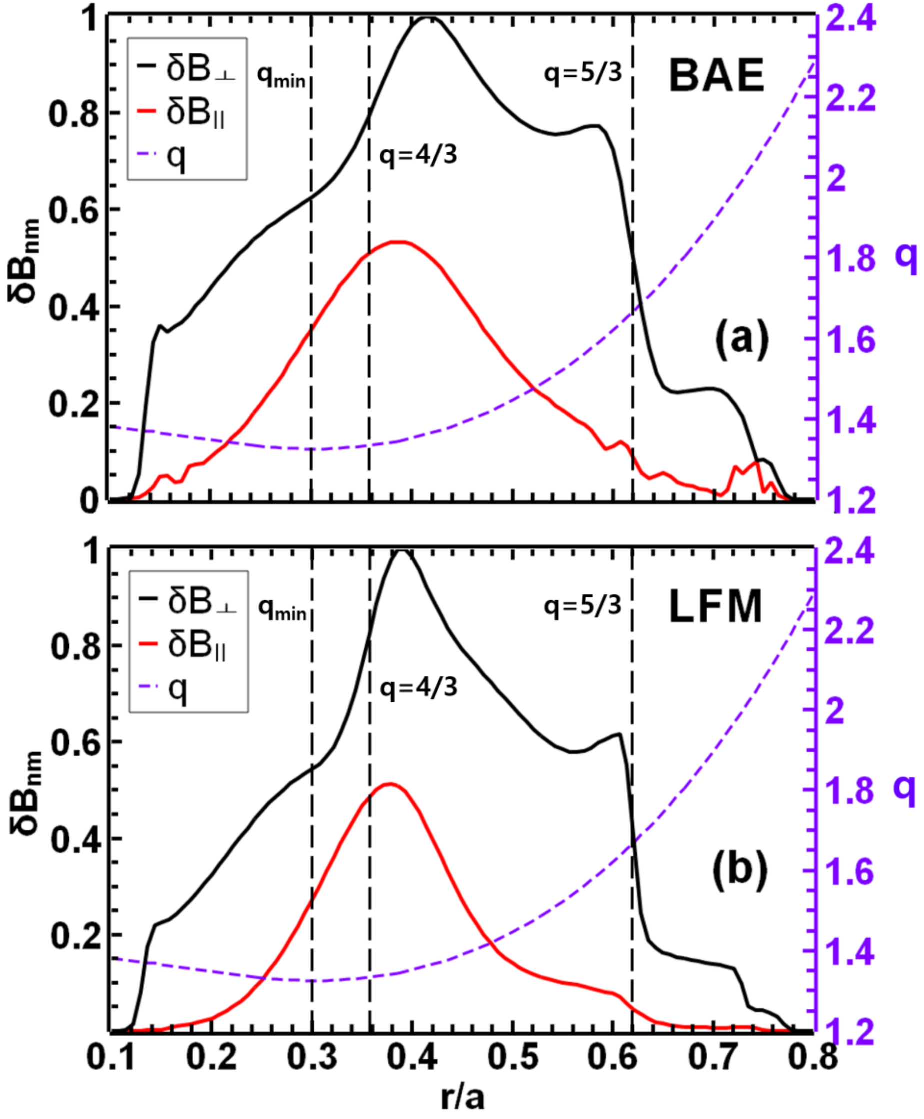
ALCON: ideal MHD continua
[W. Deng *et al.*, NF **52**, 043006 (2012)]



Further works: e.g., [I. Chavdarovski, AAPPS ‘21], [R. Ma *et al.* PPCF ‘22] (theory), [M. Xu *et al.*, NF ‘22] (exp).

Parallel magnetic compression is important

- $B_{\parallel}/B_{\perp} = 0$ for shear Alfvén wave and finite for slow modes (compressible perturbation).
- For both LFM and BAE, $\boldsymbol{B_{\parallel}/B_{\perp} \sim \mathcal{O}(1)}$, **much larger** than typical ordering $\sim\mathcal{O}(\beta)$.
- Compressible magnetic perturbation increases LFM growth rate by ~100%. (29% up for BAE)
- Compressible magnetic perturbation [G. Dong *et al.*, Phys. Plasmas **24**, 081205 (2017)] has been neglected in most of gyrokinetic codes.



GTC simulation of KSTAR #21695

- We have performed linear GTC simulations of AE in KSTAR #21695 at t=4,450ms which is in the **AE-active phase**.
- Input EFIT equilibrium and measured profiles.
- Reversed magnetic shear configuration with q_{min}~2.4.
- GTC model: GK thermal & fast ions and fluid electrons.
- Equilibrium parallel current $J_{\parallel 0}$ included.
- Maxwellian and anisotropic slowing-down equilibrium distributions.
- 200 particles per cell, $N_r \times N_\theta \times N_\parallel = 120 \times 300 \times 48$ grids.
- $n = 1 - 6$ have been simulated following KSTAR measurements.

Linear GTC finds RSAE and BAE in KSTAR

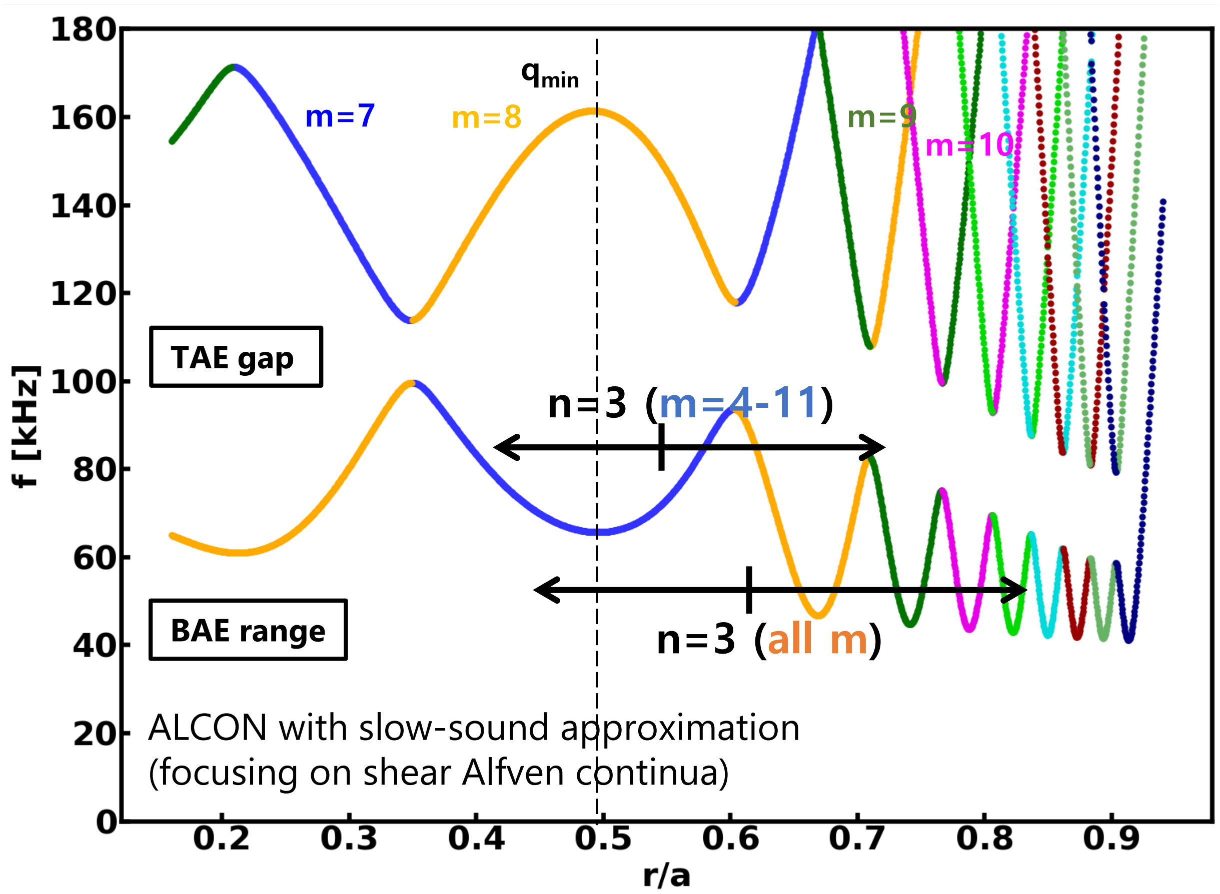
- GTC finds the most unstable $n = 3$ RSAE with $m = 4 - 11$ (84 kHz), and $n = 3$ BAE with all m (52 kHz) in KSTAR #21695.
- It's BAE which is unstable still with anisotropic slowing-down distribution function.

$$F_{SD} \propto \frac{H(v_b - v)}{1 + (v/v_c)^3} e^{\frac{(\lambda-\lambda_c)^2}{\Delta\lambda^2}} \qquad \lambda = \frac{\mu B_0}{E}$$

- $\gamma/\omega \sim 1$ for both RSAE and BAE
  $\Rightarrow$ broad resonance or
  strong non-resonant drive.

n=3	$\gamma/2\pi$ [rad/s]	γ/ω
Maxwellian RSAE (m=4-11)	44	0.52
Maxwellian BAE (all m)	45	0.86
Slowing-down BAE (all m)	76	1.6

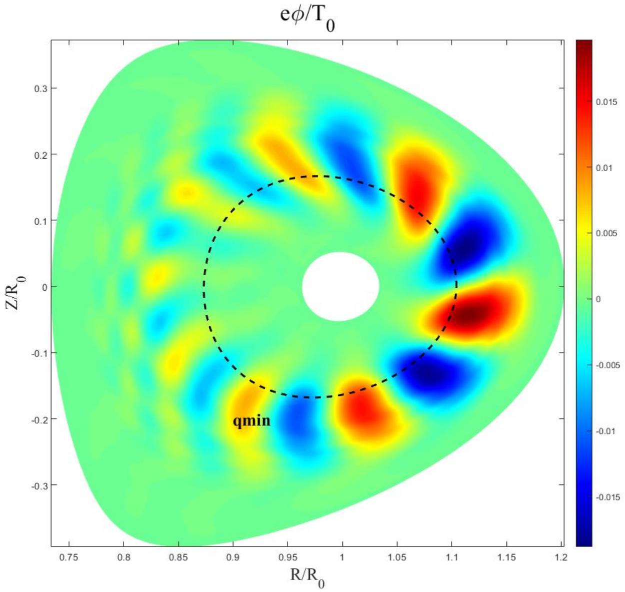
Almost the same growth rate!



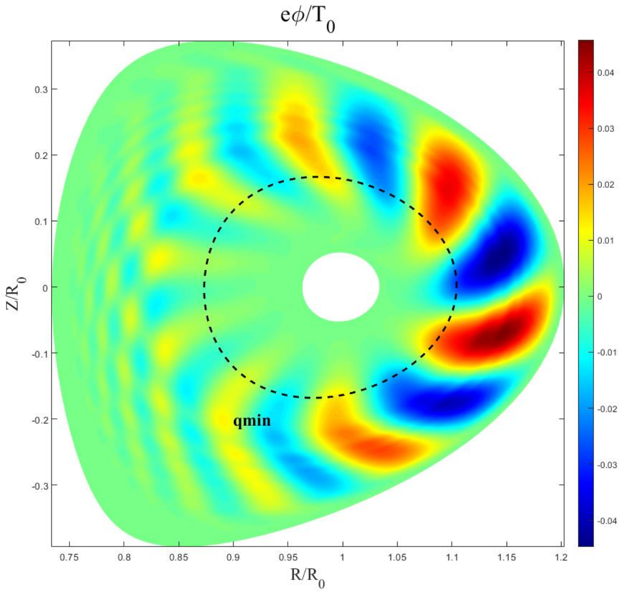
High-m harmonics important for low-n AEs

- Controlled simulations of a KSTAR plasma reveal that high-m poloidal harmonics can be important even for low-n AEs: **The most unstable mode changes dramatically**.

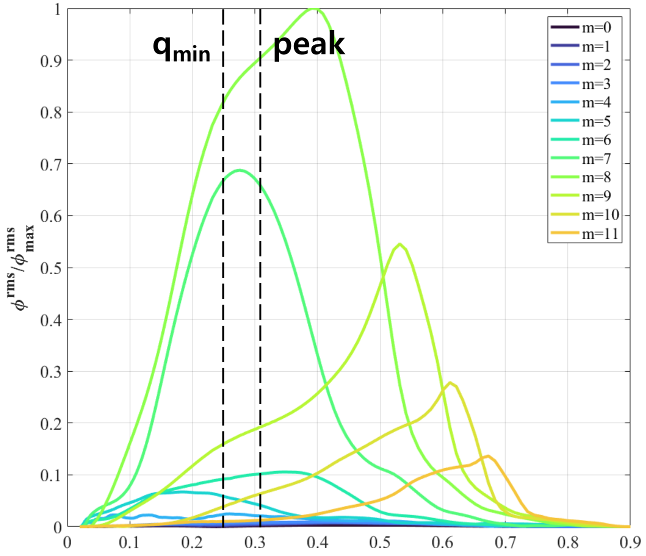
n=3 (m=4-12) **84 kHz**



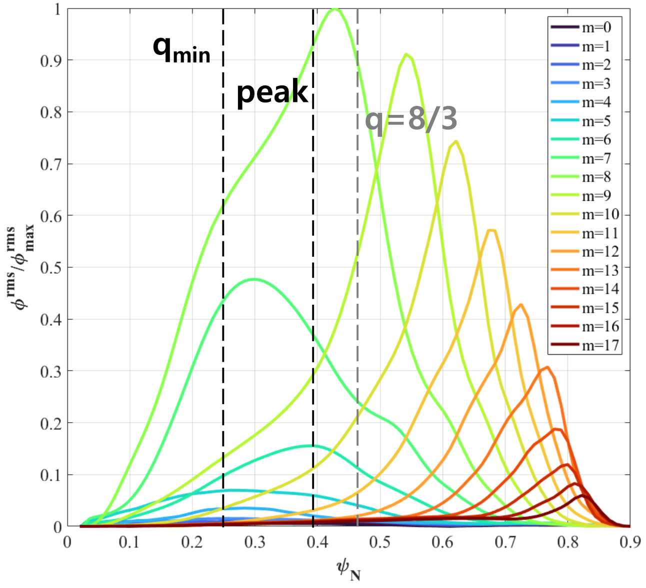
n=3 (all m) **52 kHz**



n=3 (m=4-11)



n=3 (all m)

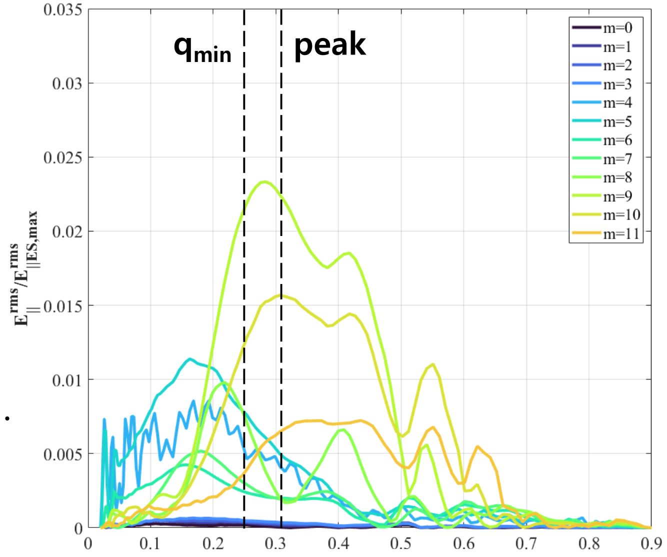


- Mode twisting by high-m harmonics. ⇒ recall $\omega_{*pf} \sim m$

RSAE/BAE deviates from Alfvenic polarization

- A polarization factor $E_\parallel / E_{\parallel,\mathrm{ES}} = 0$ for Alfvénic and 1 for acoustic, where $E_{\parallel,\mathrm{ES}} = -\nabla_\parallel \phi$.
- $E_\parallel / E_{\parallel,\mathrm{ES}} \sim 0.025$: higher than ~ 0.012 for BAE in DIII-D
  [G.J. Choi *et al.*, NF **61**, 066007 (2021)]

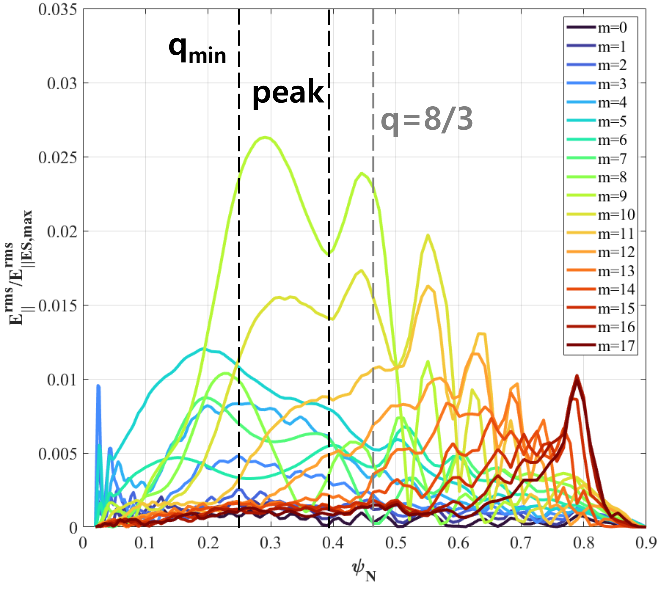
n=3 (m=4-11)



Normalized by maximum of $E_{\parallel,\mathrm{ES}}$.

- $E_\parallel$ is mostly carried by sidebands ($k_\parallel \propto m - nq$).
- It is closely related to ion Landau damping, which can play a significant role in AE stability.
- BAE peaks near the local minimum of $E_\parallel$.
  → minimizing ion Landau damping is important.
- RSAE peaks near the maximum of $E_\parallel$ (near q_{min})!
  → minimizing continuum damping is important.

n=3 (all m)



Dramatically different resonance depending on F_0

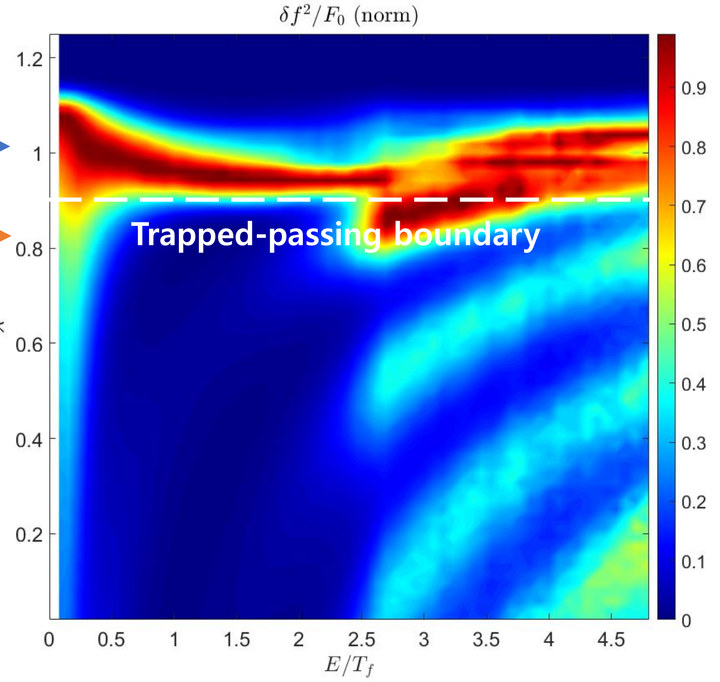
- GTC simulations with Maxwellian and anisotropic slowing-down fast ion distributions F_{f0} yield $n = 3$ BAE with very similar frequencies ~50 kHz.
- However, 2D velocity space contour plot of fast ion phase space entropy density $\delta f_f^2 / F_{f0}$ reveals that the resonance types are totally different in the two cases.
- In both cases, fast ions in a broad energy range contributes to the resonance.

Trapped fast ions →

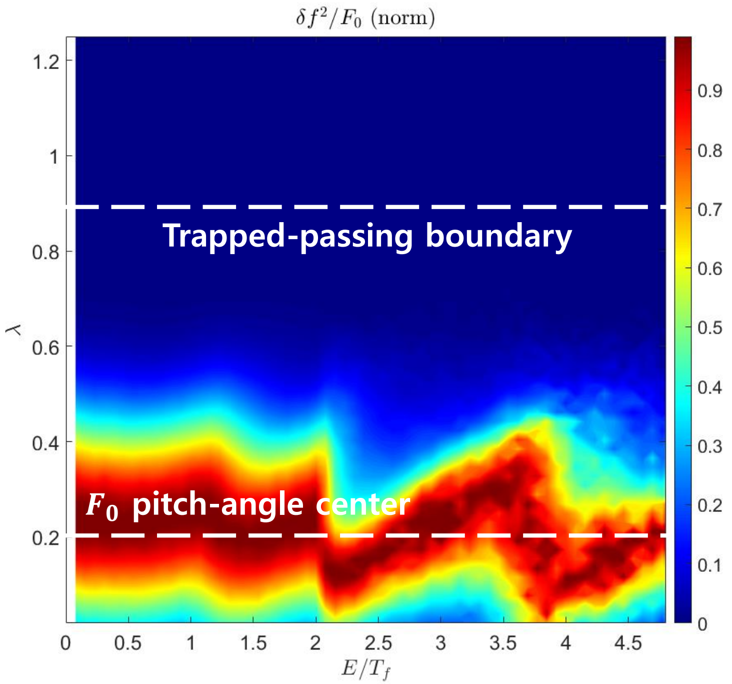
Barely passing fast ions →

$\lambda = \frac{\mu B_0}{E}$

Maxwellian



Anisotropic slowing-down



$$F_{SD} \propto \frac{H(v_b - v)}{1 + (v/v_c)^3} e^{\frac{(\lambda - \lambda_c)^2}{\Delta\lambda^2}}$$

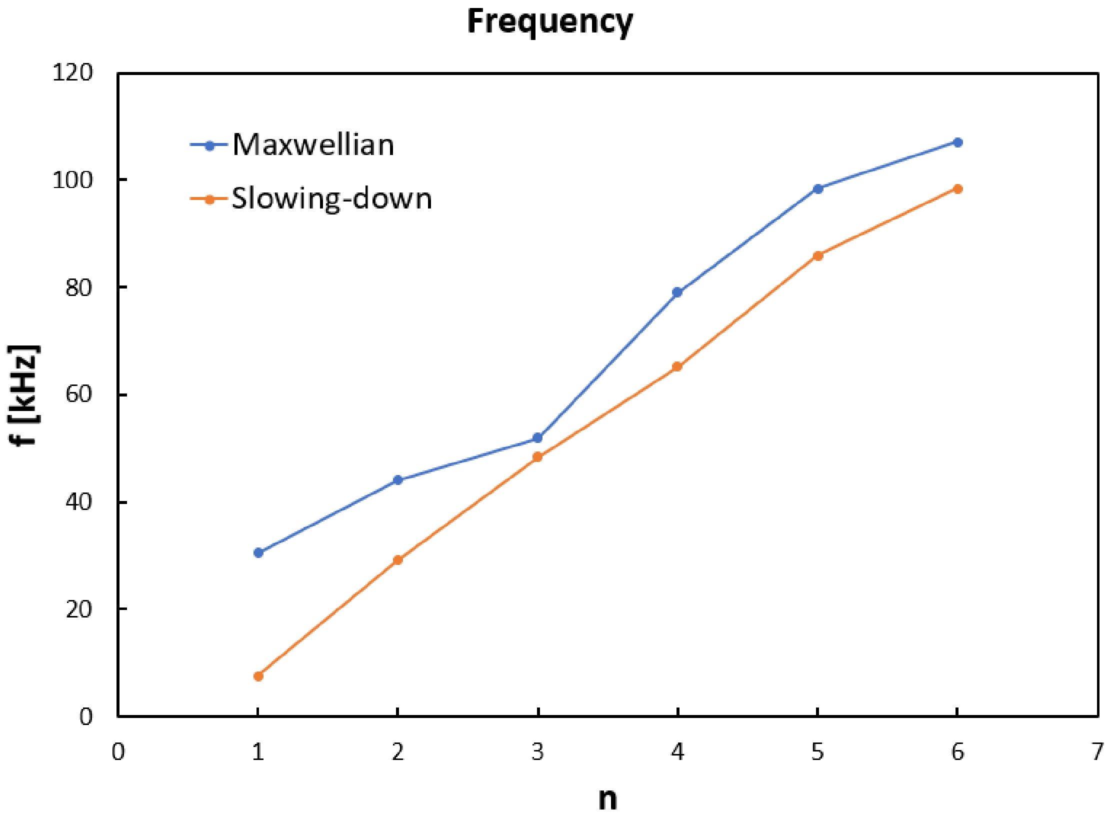
$\lambda_c = 0.2 \quad \Delta\lambda = 0.2$

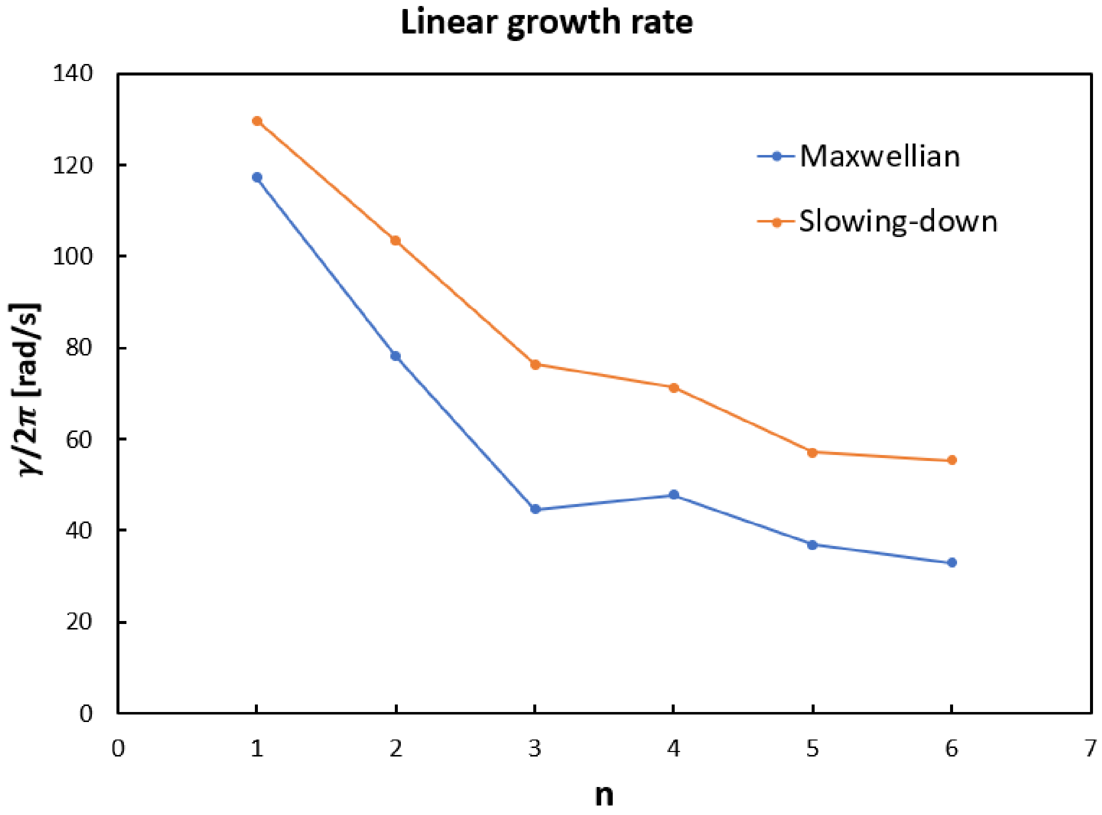
(recall co-tangential NBI in KSTAR #21695)

← **Strongly passing fast ions**

Toroidal mode number n-scan

- GTC finds gradual increase of frequency and decrease of linear growth rate with n.
- The result implies that nonlinear simulations are desired to investigate co-existence of $n = 1 - 5$ modes observed in KSTAR #21695.



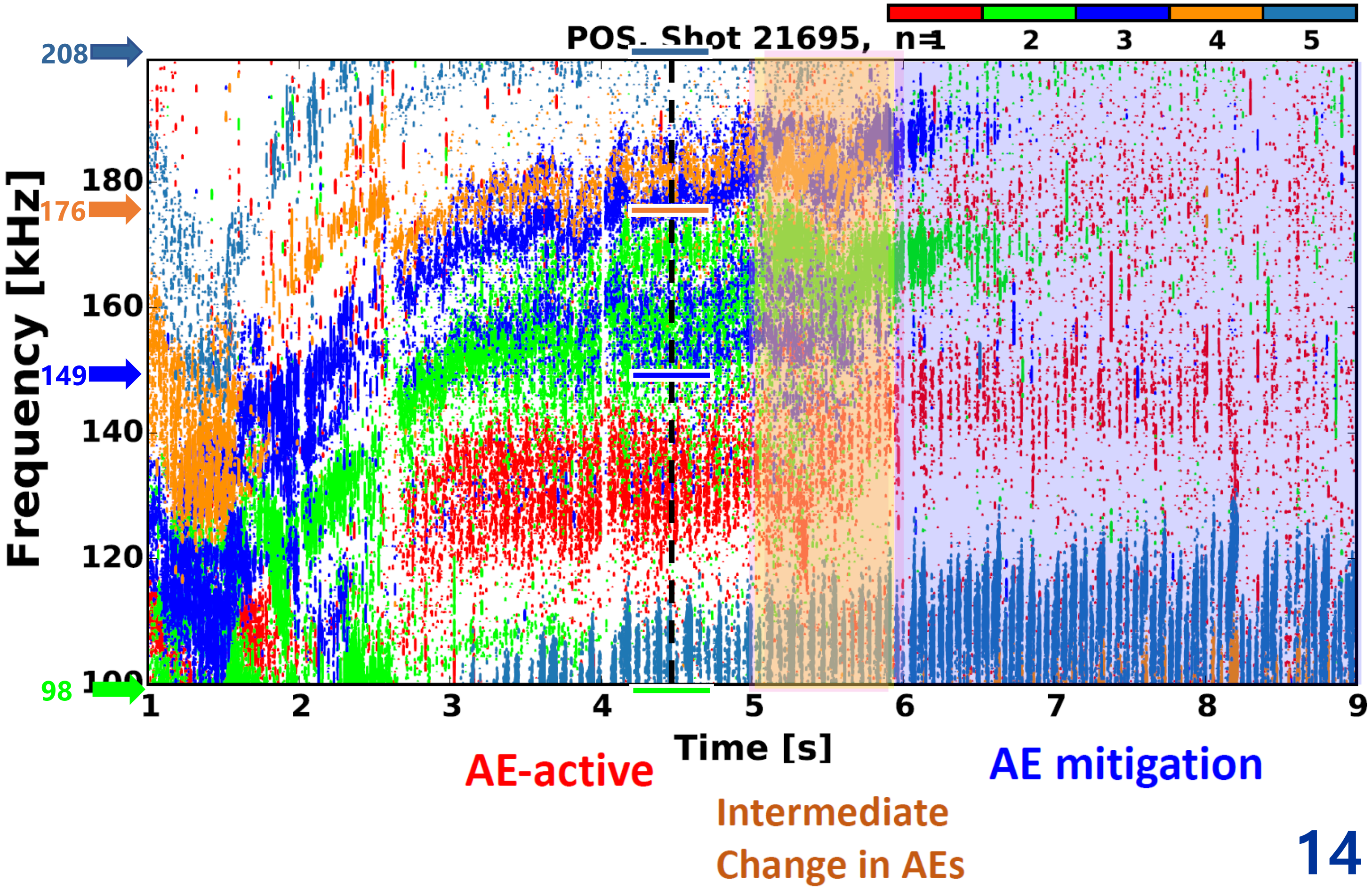


Comparison with KSTAR measurement

- AE frequencies from linear GTC with Maxwellian fast ion F_0 and finite m-harmonics agree with Mirnov coil measurement in KSTAR #21695 after Doppler shift.

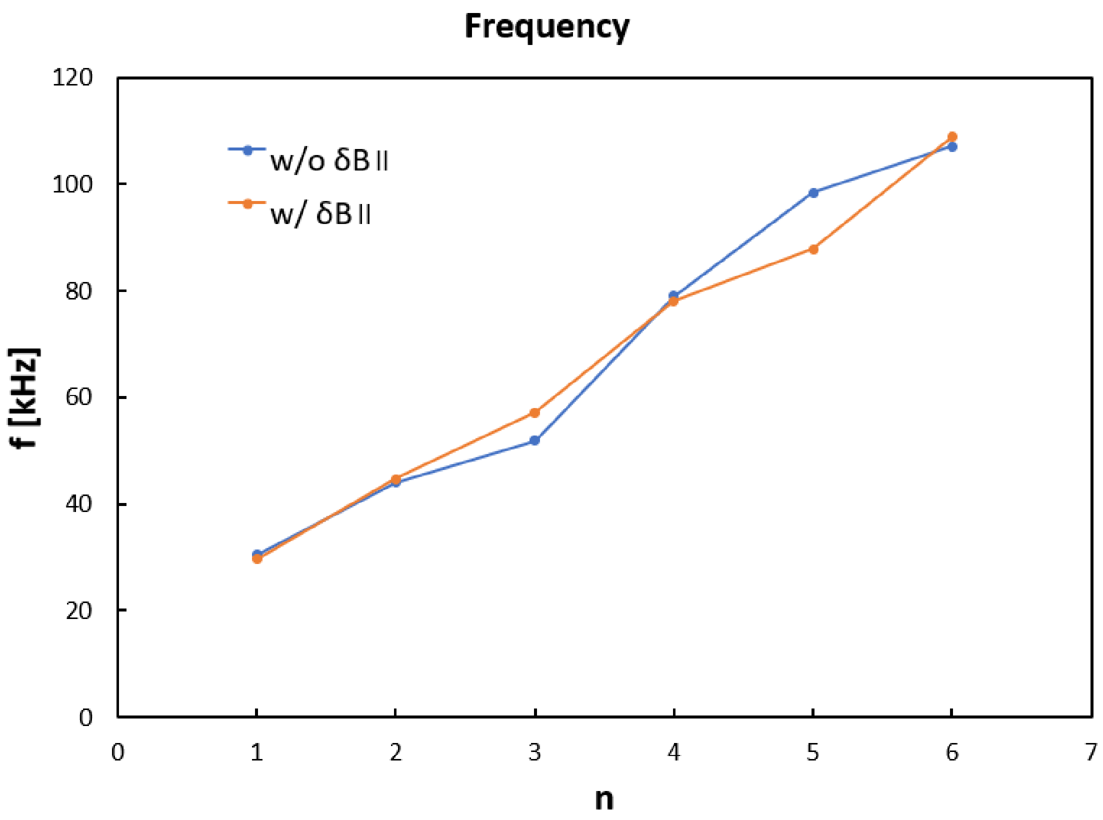
- Higher-frequency $n = 1$ and 2 modes (~ 130 and 150 kHz), $n = 3$ TAE (~180 kHz) has not been found in linear GTC.

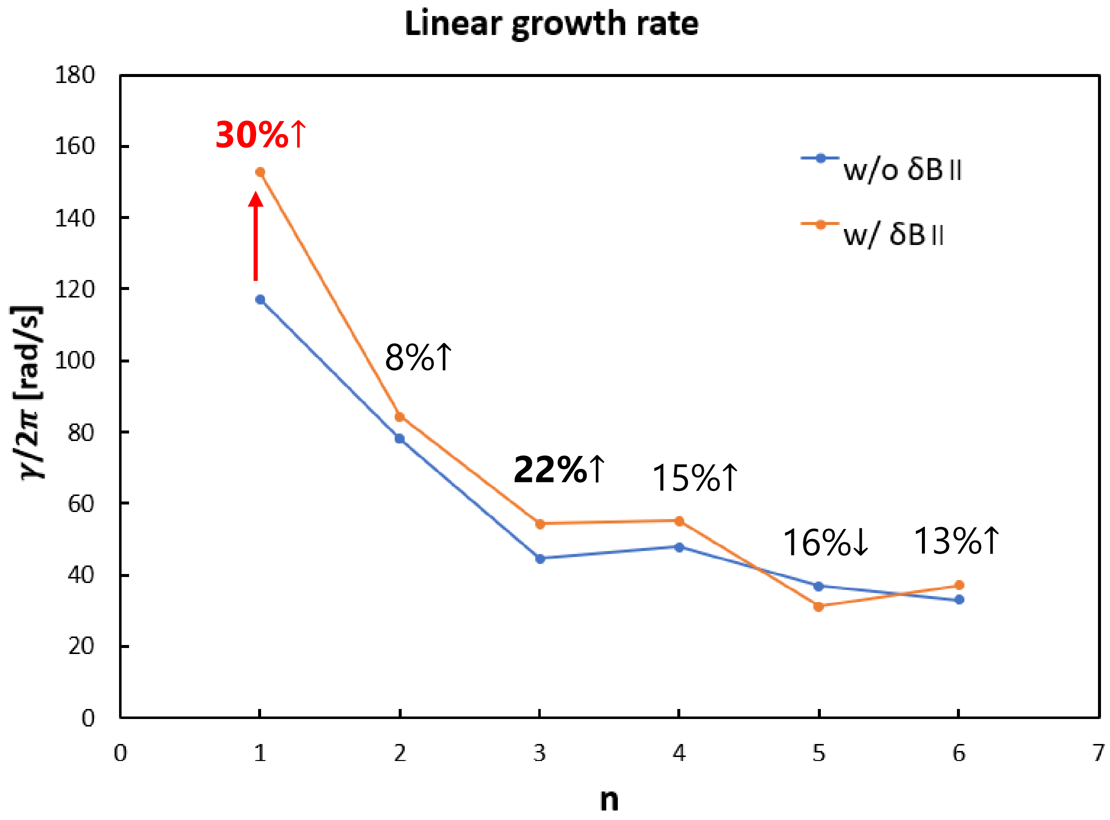
Mirnov Coil Spectogram



$\delta B_{\|}$ gives a modest change in linear growth rate

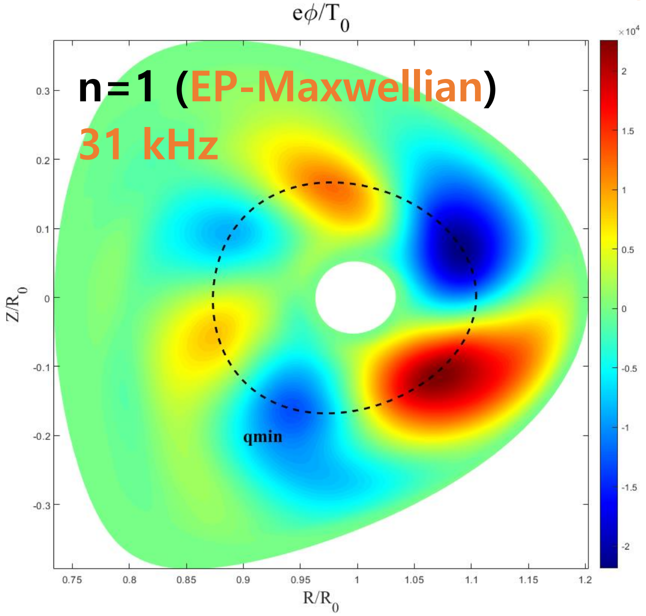
- Overall, modest change of linear dispersion by $\delta B_{\|}$ as expected [G.J. Choi *et al.*, NF '21].
- $n = 1$ mode shows the most significant $\delta B_{\|}$-destabilization.

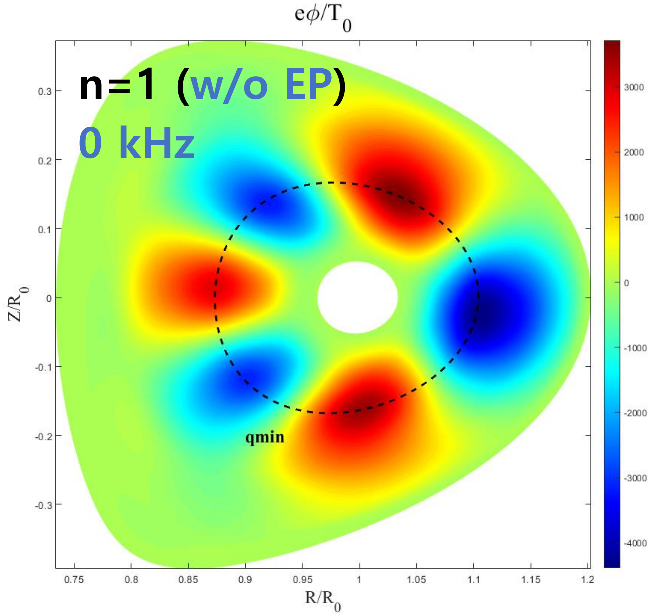


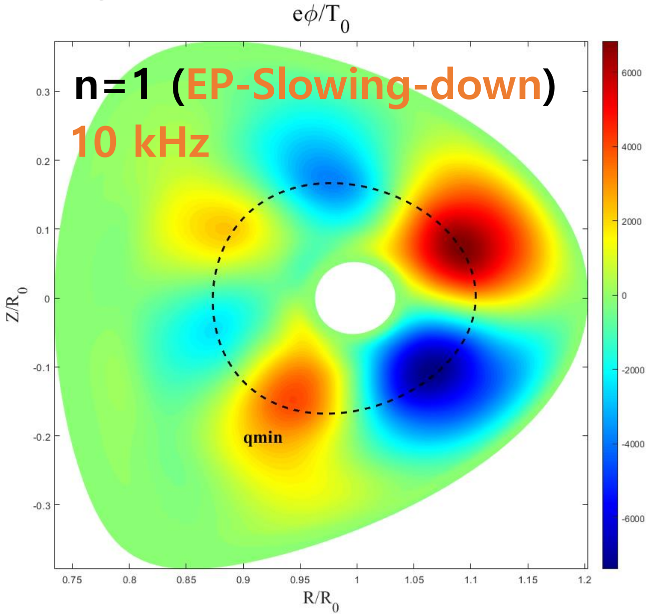


GTC found current-driven 3/1 mode at q_{min}

- GTC **without fast ions** find a robust $n = 1$ ideal MHD instability **peaking at q_{min}**.
- The same simulation without equilibrium parallel current $J_{0\parallel}$ didn't find a growing mode.
  $\Rightarrow$ **3/1 current-driven ideal MHD mode !**
- Higher growth rate (by 33%) from GTC incompressible MHD simulation: stabilizing role of $E_\parallel$.
- Minor role of $\delta B_\parallel$ w/o EP: almost no change in the linear growth rate. (Recall 30% up w/ EP.)
- **EP** makes the mode more unstable (by 18%(Max), 37%(Slowing-down)), distorts its shape and makes it more ballooning (i.e., stronger toroidicity-induced coupling), and rotates it.

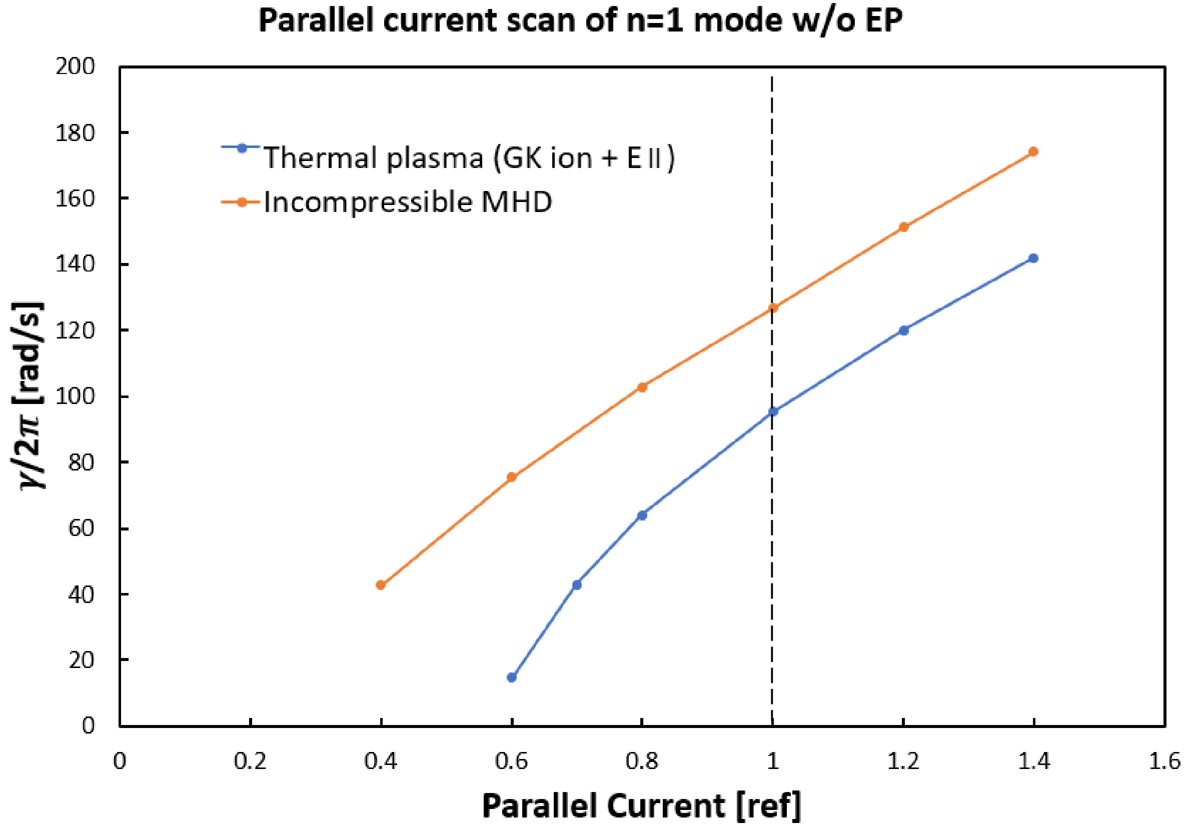




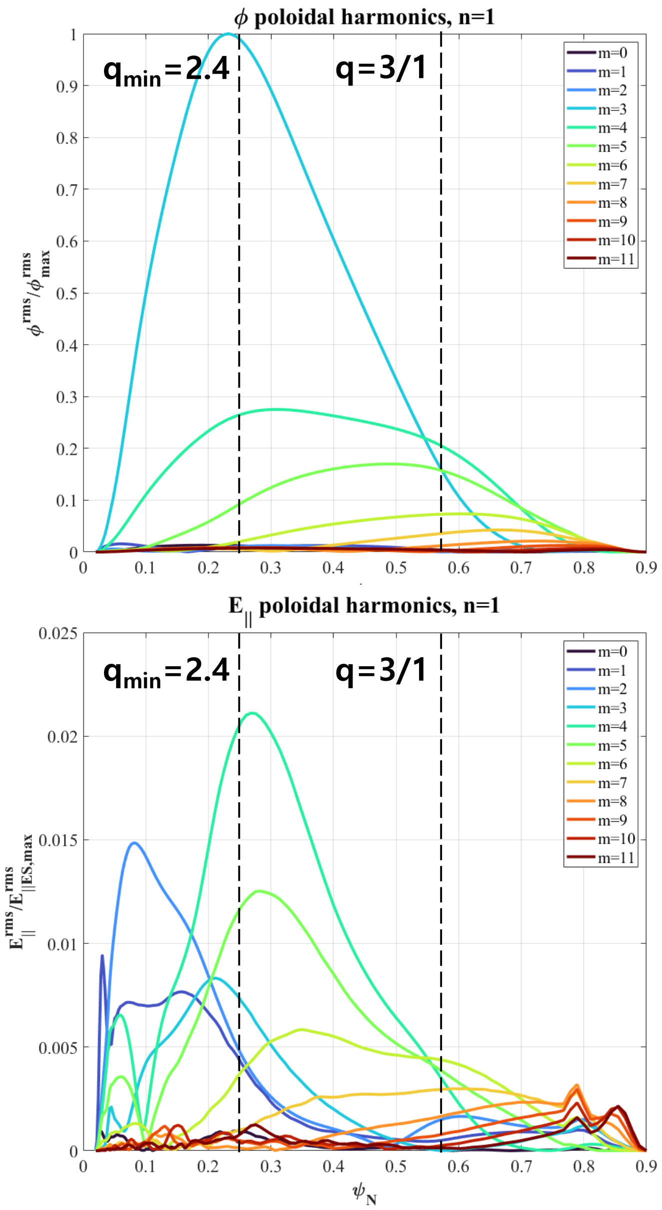


GTC found current-driven 3/1 mode at q_{min}

- Stability strongly depends on parallel current $J_{0\parallel}$.
- With $J_{0\parallel}$ but w/o ∇P (uniform profiles): γ ↘ to 48%.
  ⇒ significant contribution from ∇P, though not necessary.
- Further analysis on this ideal 3/1 mode will be interesting.



Parallel current scan of n=1 mode w/o EP



Next step: Turbulence simulation

- To achieve our final goal (nonlinear gyrokinetic simulations of AE with microturbulence in KSTAR plasmas), we performed linear n-scan of microturbulence.

- Although we miss some higher-frequency AEs in KSTAR #21695 from linear GTC, this doesn't bring a big issue into our plan. Recall that most of low-n AE signals, including multiple $n = 3$ lines, disappeared together by ECCD.

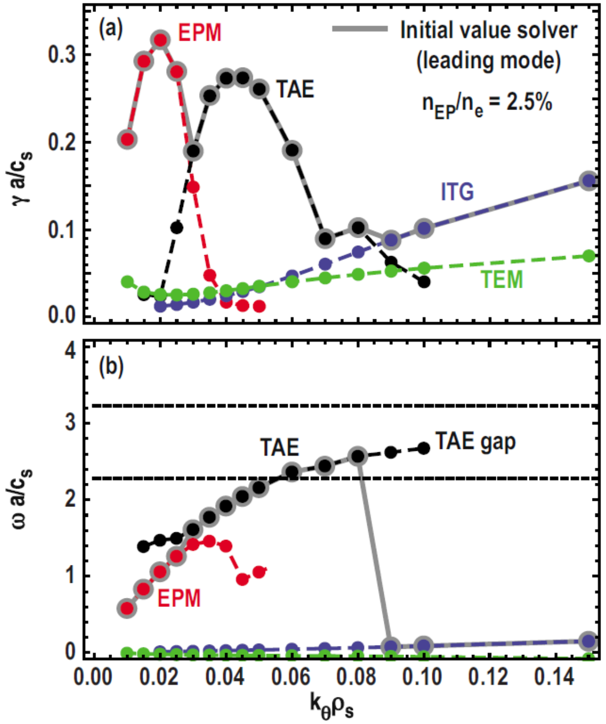
- Since GTC global nonlinear multi-n simulations are extremely heavy and sensitive to numerical settings, preceding GKW [1] local simulations could be helpful for an extensive study of the AE-turbulence nonlinear interactions.

[1] A.G. Peeters *et al.*, CPC **180**, 2650 (2009)

Local GK simulation can be useful for AE study

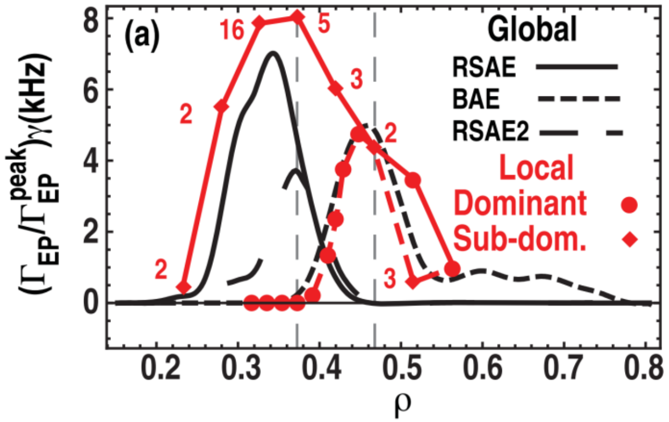
- While local gyrokinetic simulations miss rich non-local physics in EP-AE interplay, it could capture some important features of EP-AE-turbulence systems.

Multiple excitation of EPM, TAE, ITG and TEM can be analyzed.

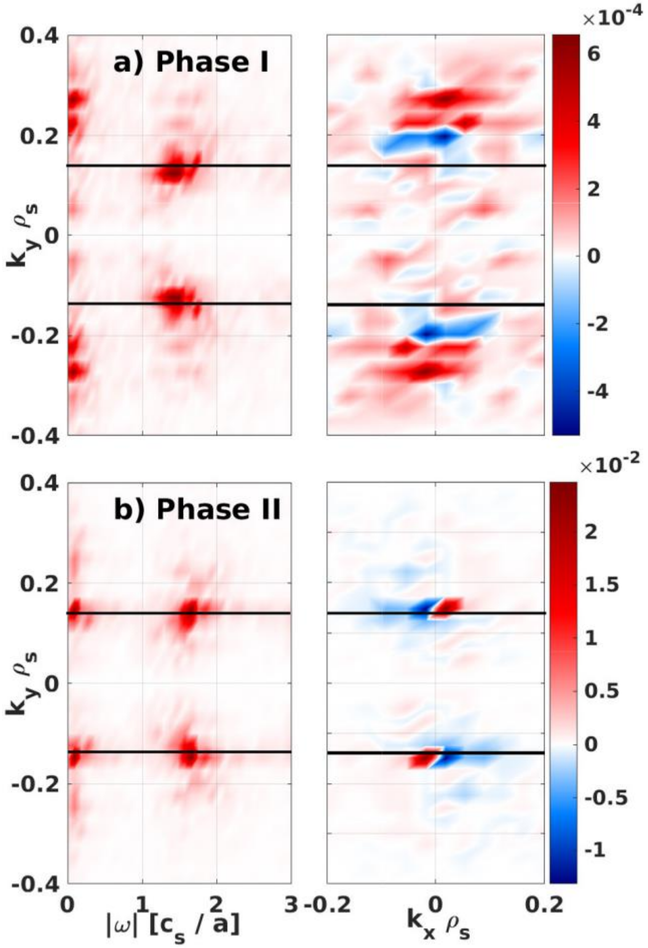


[E.M. Bass and R.E. Waltz, PoP **17**, 112319 (2010)]

Local and global predictions of EP transport flux are comparable after being properly normalized.



[E.M. Bass and R.E. Waltz, PoP **20**, 012508 (2013)]



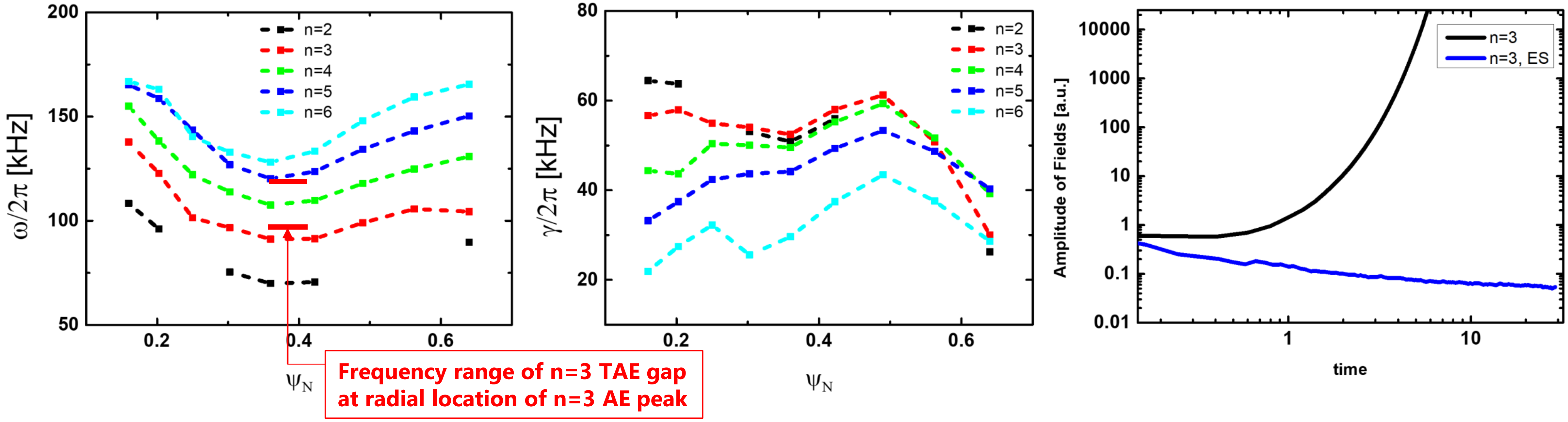
Marginally stable TAE can suppress turbulence becoming a dominant mode interacting with zonal flows.

[A. Di Siena *et al.*, NF **59**, 024001 (2019)]

Also, recent works by S. Mazzi

GKW also finds AEs in KSTAR #21695

- GKW local simulation finds $n = 3$ mode having frequency ~ 85 kHz near the radial location of TAE gap, just below the TAE gap frequency. It is **similar with the result from the GTC** global simulation (RSAE/BAE).

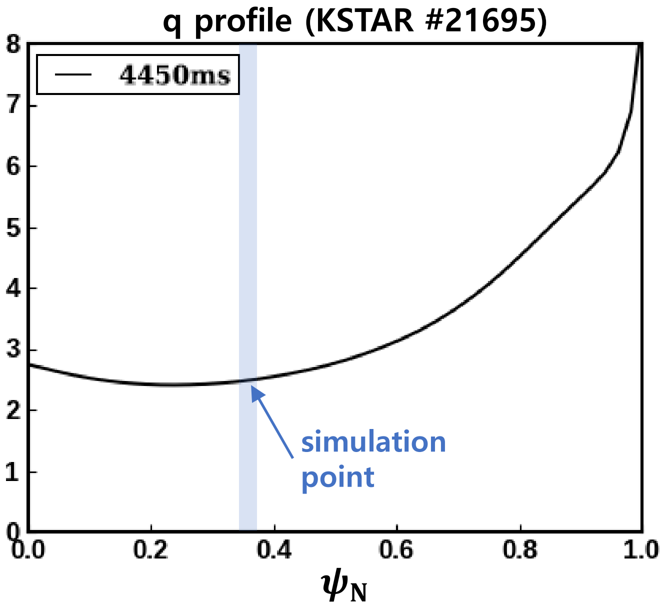


Frequency range of n=3 TAE gap at radial location of n=3 AE peak

- Frequency difference of GKW from GTC decreases with n ($n = 4$: +20 kHz, $n = 5$: +11 kHz).
- Gradual frequency increase and linear growth rate decrease obtained from GKW local simulations are consistent with GTC global simulation results.

Linear GKW n-scan of KSTAR #21695

- GKW local simulation of KSTAR #21695 on $\psi_N = 0.36$ (near n=3 AE peak) at t = 4,450 ms (AE-active phase).



- Input EFIT equilibrium and measured profiles:

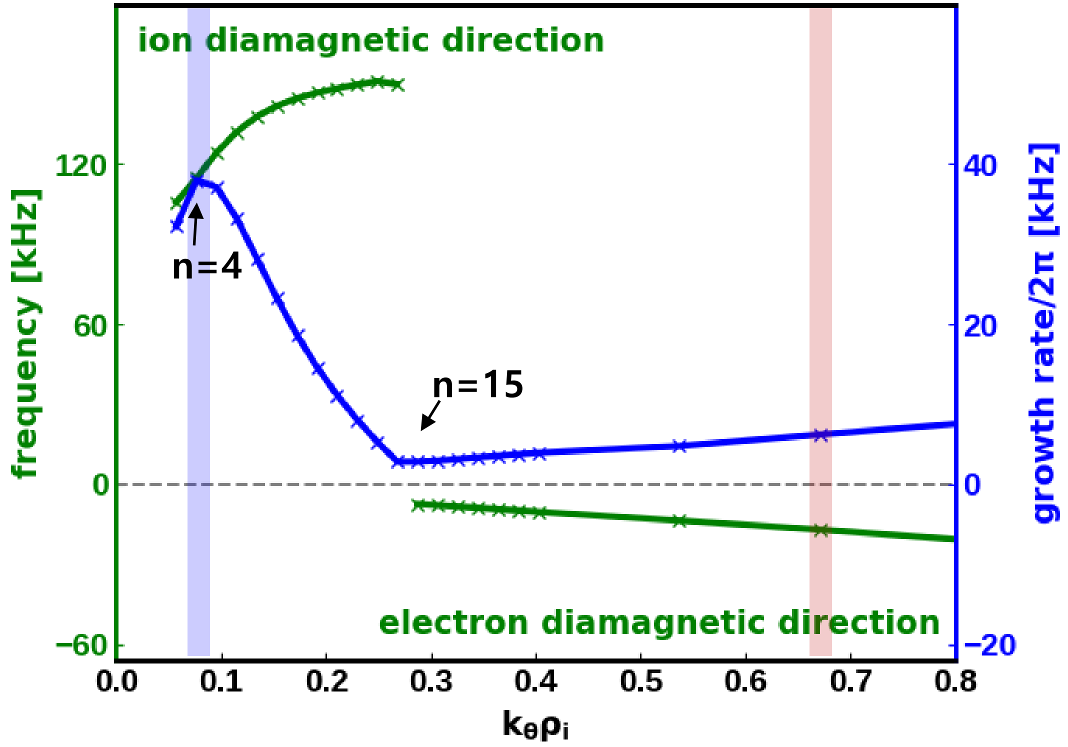
  $R/L_{n_e} = 0.89$, $R/L_{T_e} = 8.1$, $R/L_{T_i} = 2.9$, $T_e/T_i = 1.2$, $T_f/T_i = 30$

- GK thermal & fast ions and GK electrons
- Electromagnetic fluctuations $\delta A_\parallel, \delta B_\parallel$ are kept.
- Grids: $N_x \times N_z = 23\times64$, $N_{v_\parallel} \times N_\mu = 64\times48$.
- $n = 3 - 3000$ has been scanned which cover from ion-scale down to electron-scale. ($k_\theta\rho_i \approx 1$ at $n = 50$ and $k_\theta\rho_e \approx 1$ at $n = 3000$)
- Maximum radial box size $L_x \approx 20\rho_i$ at $n = 3$ (minor radius $a \approx 115\rho_i$).

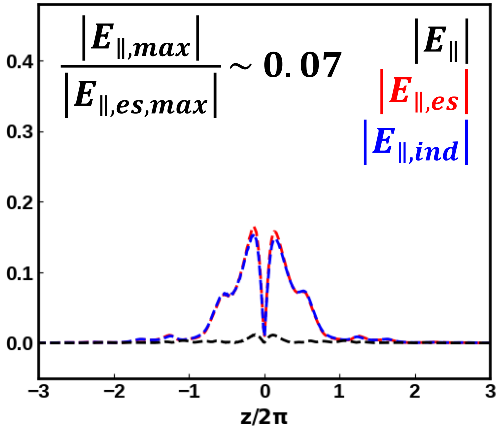
Ion scale mode transition at n=15

- **The direction of mode propagation flips at $n = 15$,** indicating that low-n modes are fast ion-driven Alfvenic modes and high-n modes are trapped-electron modes (TEMs).

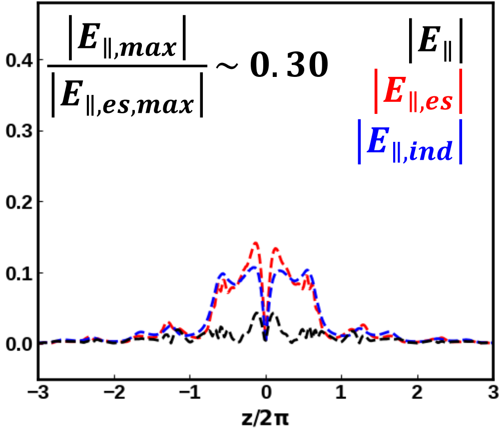
- Polarization shows that low-$n < 14$ modes are electromagnetic (Alfven wave-like) and higher-$n \geq 15$ modes are electrostatic (drift wave-like).



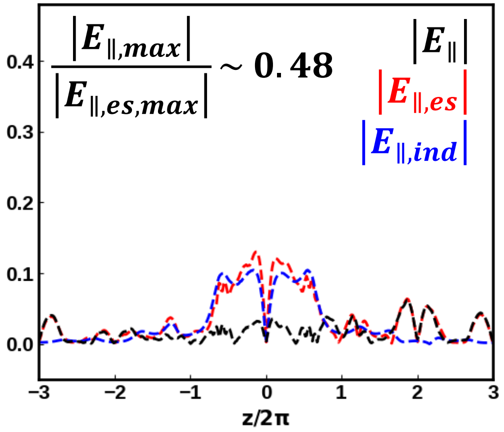
n = 4 ($k_\theta \rho_i$=0.08)



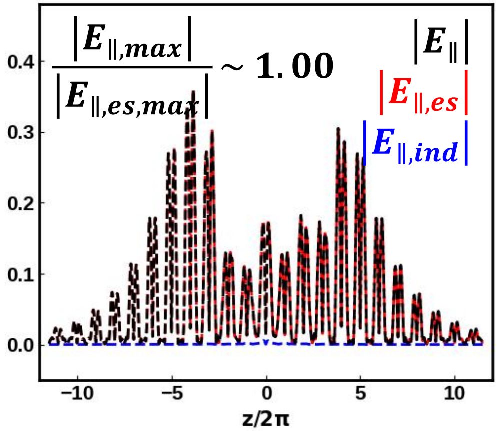
n = 13 ($k_\theta \rho_i$=0.25)



n = 14 ($k_\theta \rho_i$=0.27)

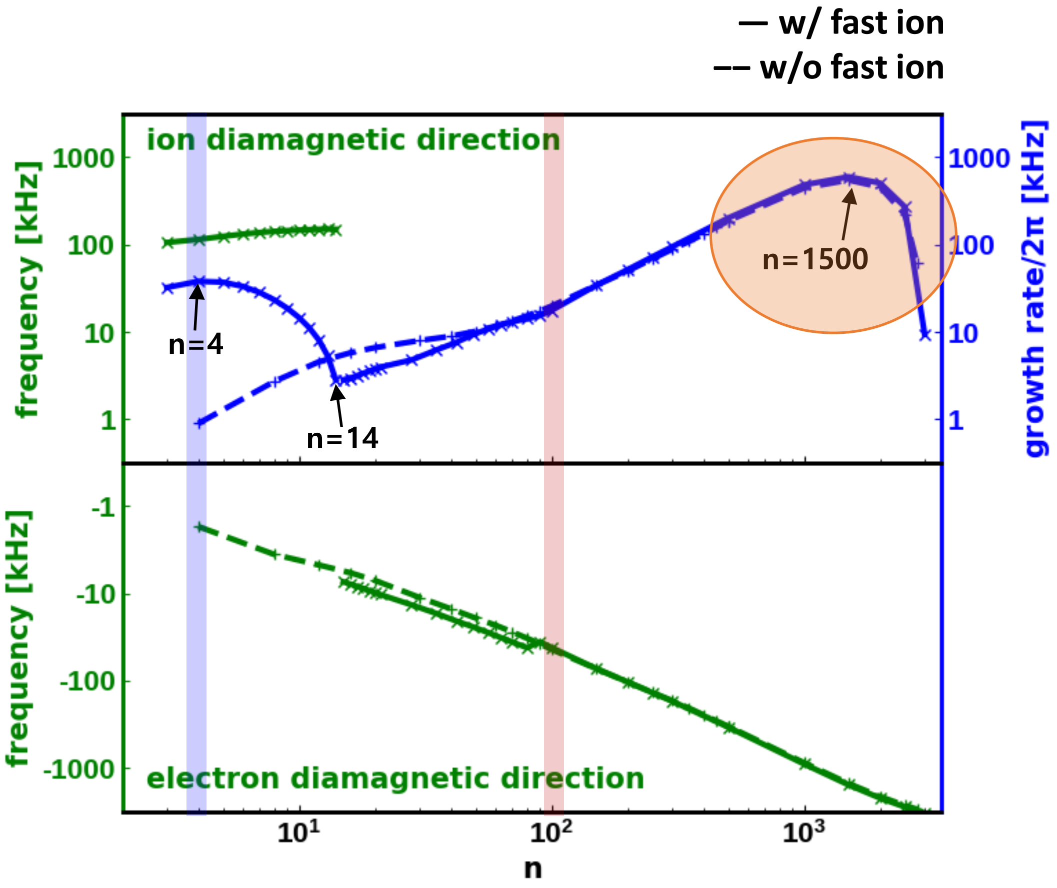


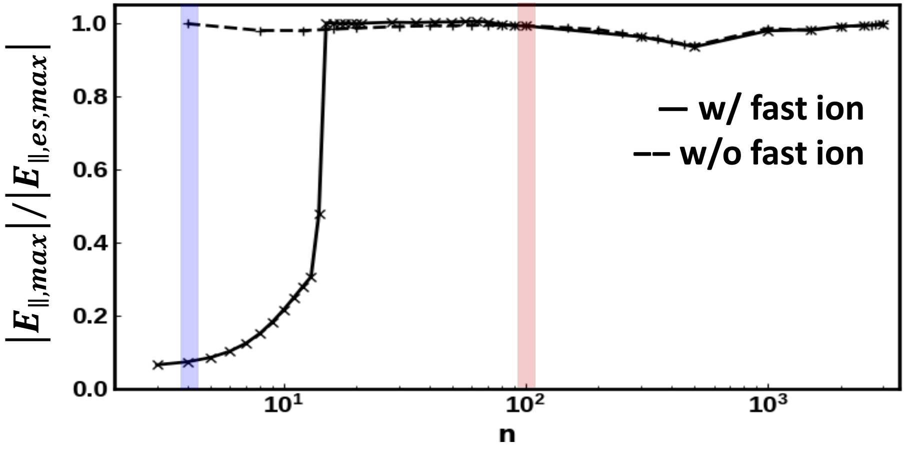
n = 15 ($k_\theta \rho_i$=0.29)

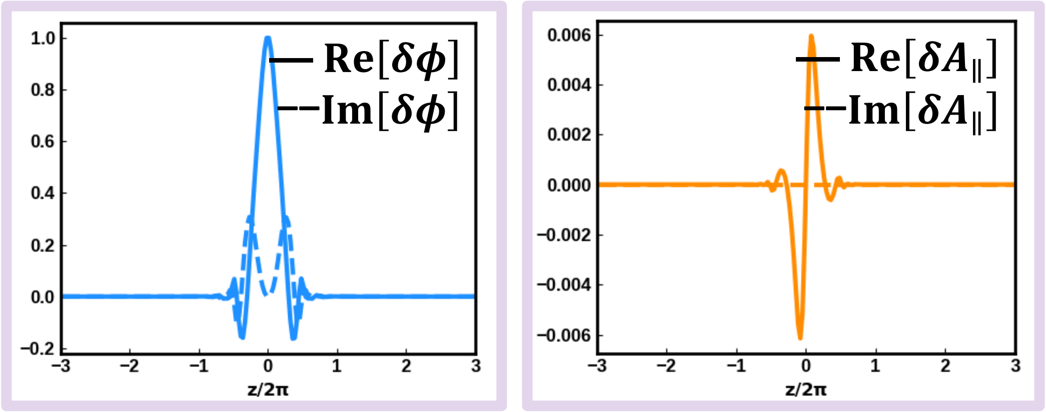


Electron scale mode is the most unstable

- Linear GKW finds the **most unstable mode in the electron scale** $k_\theta \rho_e \sim 1$.
- Frequency, polarization and mode parity shows that this is **ETG mode** (not MTM).



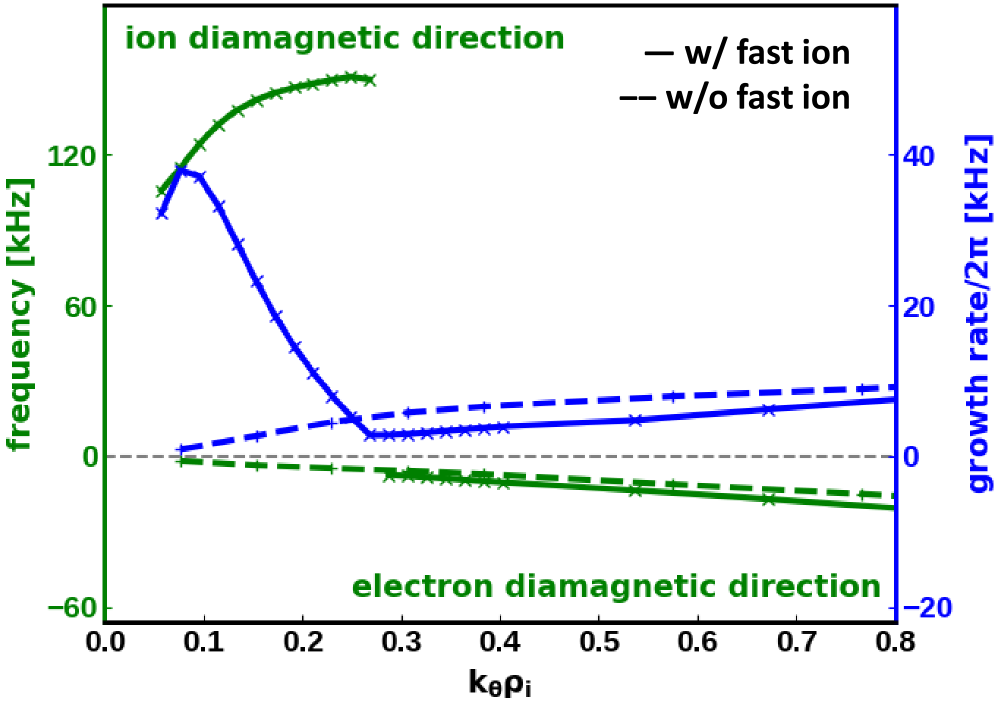


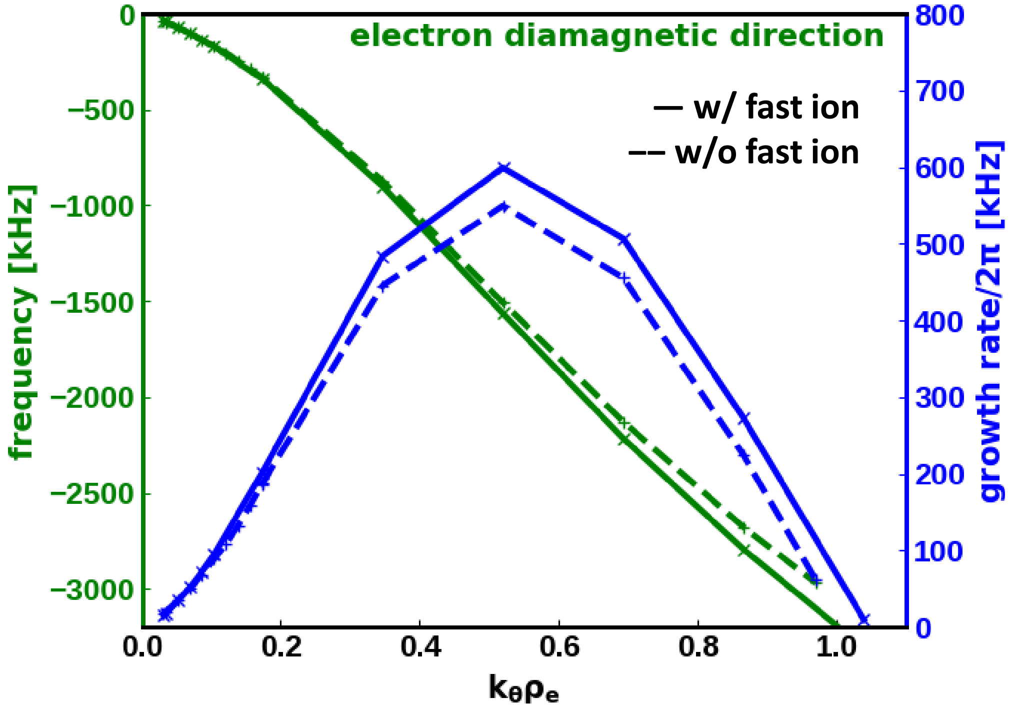


n=1500 ($k_\theta \rho_e$=0.52)

Fast ion effect on linear mode stability

- In ion scale, GKW without fast ions finds low-n modes propagating in the electron direction (TEM), with much lower growth rate compared to the case with fast ions.
- Fast ion effects on linear stability of turbulence modes are modest overall: fast ions stabilize TEM, while they destabilize ETG.





Summary

- We have presented results of ongoing study of AE-turbulence interactions in KSTAR.
- We have performed linear gyrokinetic simulations of KSTAR #21695 at t=4,450ms using GTC global code and GKW local code to find and study AEs.
- With a reversed q-profile, linear GTC and GKW find the most unstable RSAE & BAE.
- Different fast ion distribution functions (Maxwellian, anisotropic slowing-down) result in similar BAE frequency, while the resonance type is completely different.
- **Both GTC and GKW** show gradual increase of frequency ω and decrease of linear growth rate γ with toroidal mode number n.
- GTC reveals that the most unstable KSTAR $n = 1$ mode is not an EP-driven AE. It is rather a current-driven 3/1 ideal MHD mode peaking at q_{min}.
- Linear GKW scan finds that **ETG mode is the most unstable** dominating over BAE and TEM. Fast ions destabilize the ETG, but the effect is modest.
- Future work: nonlinear GKW & GTC simulations to study AE-ETG interactions.