MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Global electromagnetic gyrokinetic modelling of Energetic Particle driven instabilities in ITER and ASDEX Upgrade

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EUROfusion

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Outline

Energetic Particle (EP) physics

Numerical model: the ORB5 Code

ITER PFPO scenario (101006)

- Scenario description
- Low-n AEs
- Meso-n AITGs

ASDEX Upgrade ‘NLED-AUG’ scenario (#31213)

Introduction: Energetic Particle physics

- Energetic particles in tokamak plasmas:
  - Alpha particles, born from fusion reactions (3.5 MeV)
  - NBI ions, injected (anisotropically) at, e.g. ITER: $\sim$1 MeV
  - ICRH ions, drawing out tails, $T_\perp > T_\parallel$
- Often modelled with simple distribution functions, e.g.:
  - (local) Maxwellian
  - Bump-on-tail
  - Slowing down
- Can be treated more realistically with:
  - Analytical anisotropic (e.g. anisotropic slowing down)
  - Numerical distributions from heating codes

Must be confined long enough to heat up plasma.

Introduction: Energetic Particle physics

Energetic particles can drive plasma instabilities, especially Alfvén eigenmodes (AEs), such as TAEs (Toroidal AE).

Consequences of instabilities:

- EP redistribution: less effective heating or particle losses
- Modification of bulk plasma profiles
- Intermediate coupling to Macro-scale (MHD) or Micro-scale (turbulence)

Challenging modelling problem, AEs are electromagnetic and global modes; mode drive and damping is resonant (kinetic).

This work uses NL GK simulation to address EP/AE physics. See talk in this session by M. Falessi for theory-based reduced models.

ORB5[1]

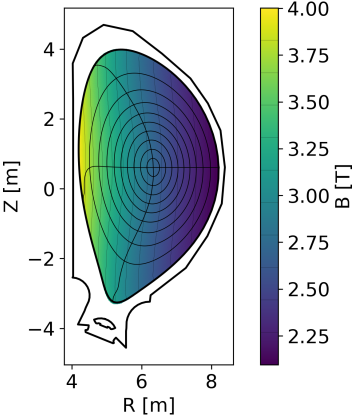
"ORB5: a global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry"

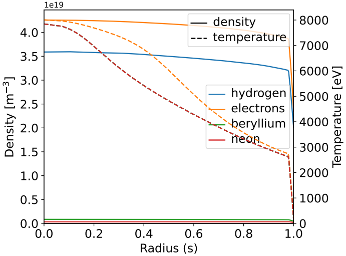
- Fields solved using finite elements (cubic B-Splines)
- Filter applied in toroidal and poloidal mode numbers
  - $m(r) = nq(r) \pm \Delta m$
- Effectively mitigates with the so-called cancellation problem using the pullback scheme [Mishchenko 2019]
- Gyrokinetic ions, drift-kinetic electrons ($m_i/m_e \geq 400$)
- Previously used for turbulence studies as well as EP physics
- International AE benchmarking activities:
  - e.g.: ITPA-TAE benchmark, DIII-D RSAE/TAE benchmark
  - benchmarking activities used local Maxwellian for EPs
- Recent developments for numerical and semi-analytical distribution functions

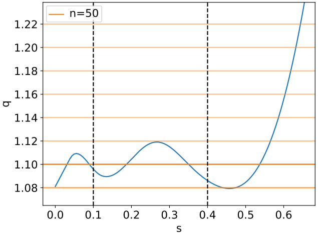
[1] for details, see Lanti+ CPC 2020

ITER PFPO-2 Scenario (IMAS: 101006#50)[2]

Pre-fusion-power-operation.
Half current. Half field.



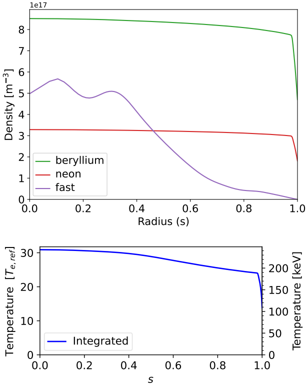




[2]Polevoi+ 2021; ITPA B.11.12

ITER PFPO-2 EP profiles

- 2 N-NBI sources at approx 1 MeV injection energy (1 on-axis, 1 off-axis)
- Small density, $n_{EP} = 0.5 \cdot 10^{18}$ m^{-3} on axis, cf. $n_H = 3.6 \cdot 10^{19}$ m^{-3}
- Equivalent temperature with 1 MeV slowing down approximation $T_{EP} \sim$ 200 – 250 keV, $\approx 30 \times T_e$

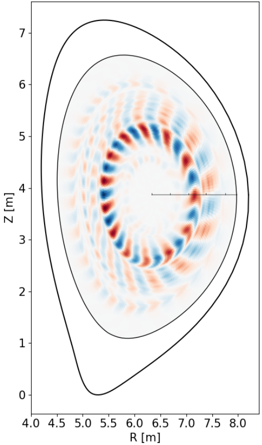


We consider nominal and double EP densities using isotropic slowing down

ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

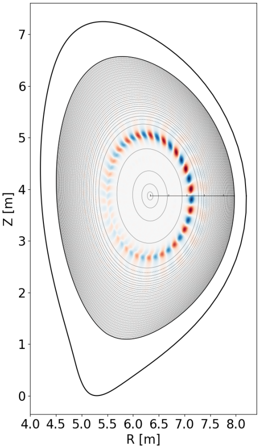
n=12 (BAE)



ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

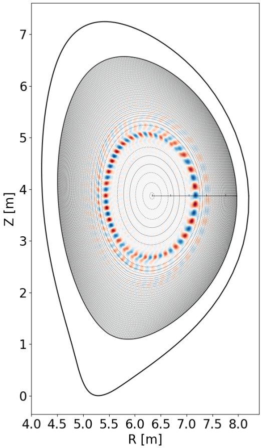
n=20 (TAE)



ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

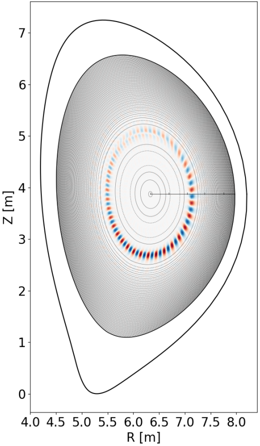
n=26 (EAE)



ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

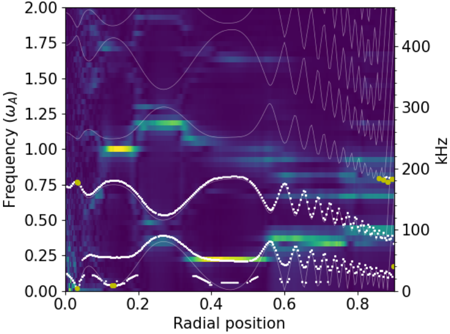
n=32 (RSAE)



ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

n=12 (BAE)



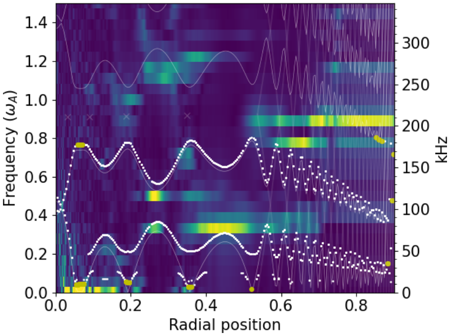
n=12

Alfvén continuum from ligka (thick: kinetic)

ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

n=20 (TAE)



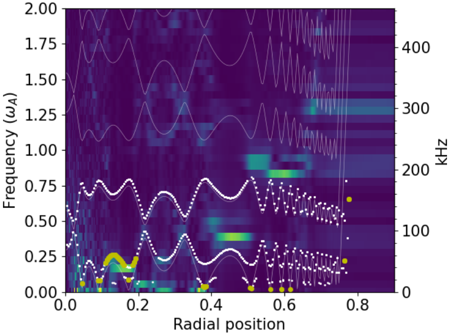
n=20

Alfvén continuum from ligka (thick: kinetic)

ITER PFPO without EPs

AEs in the absence of EPs (stable, weakly damped)
TAEs, EAEs, lower frequency (RSAE and/or BAE)

n=32 (RSAE)



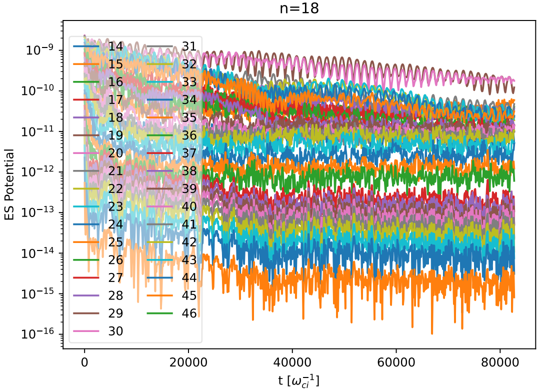
n=32

Alfvén continuum from ligka (thick: kinetic)

ITER PFPO with EPs

Adding EP distribution, introduce AE drive

E.g. n=18

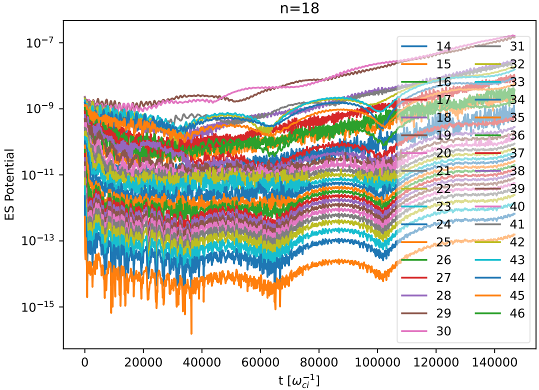


Nominal EP density not enough to drive AEs

ITER PFPO with EPs

Adding EP distribution, introduce AE drive

E.g. n=18

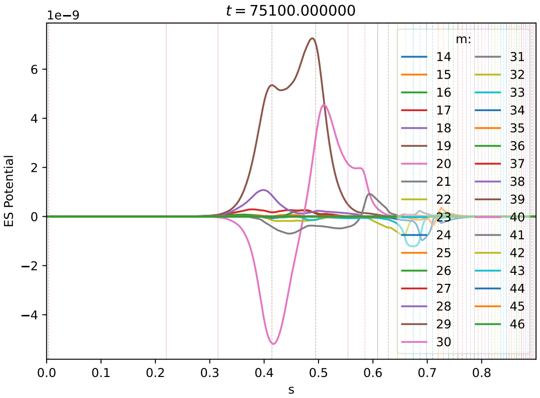


2x n_{EP}, growing beating mode(s)

ITER PFPO with EPs

Adding EP distribution, introduce AE drive

E.g. n=18

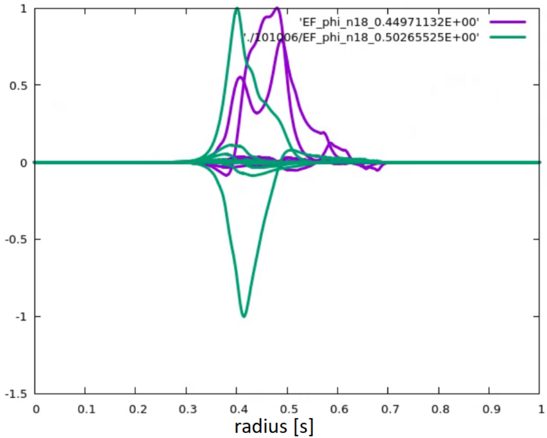


2x n_{EP}, twin TAE locations at $s \sim [0.414, 0.495]$

ITER PFPO with EPs

Adding EP distribution, introduce AE drive

E.g. n=18

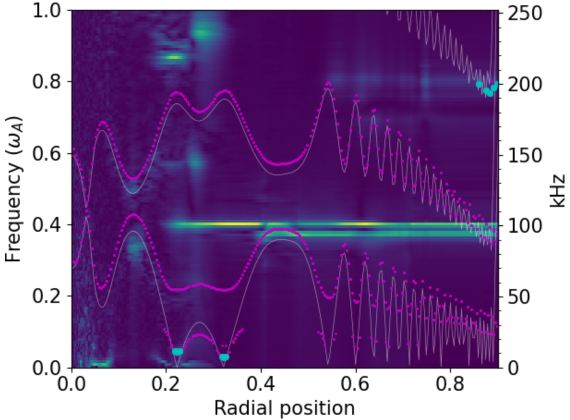


Twin TAEs found by LIGKA, mixed parity

ITER PFPO with EPs

Adding EP distribution, introduce AE drive

E.g. n=18



2x n_{EP} (n.b. Continuum mismatch: q_{LIGKA} vs q_{ORB5})

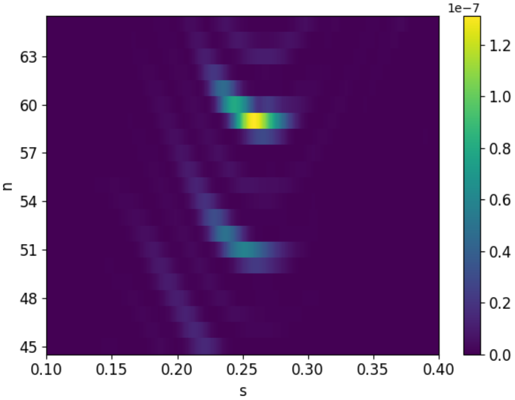
ITER PFPO without EPs (meso-n BAEs/AITGs)

Increasing the mode number, looking for other kinds of Alfvénic instabilities

ITER PFPO without EPs (meso-n BAEs/AITGs)

Higher-n core BAEs/AITGs (Alfvénic ITG) in the absence of EPs (driven **unstable** by **bulk** plasma[3])

Low frequency: in range $40 < n < 70$ (γ depends on distance between rational and q-extrema)



several single-n simulations $|\phi(s, n)|$ on outboard midplane

[3]Zonca+ 1996; 1998

ITER PFPO without EPs (meso-n BAEs/AITGs)

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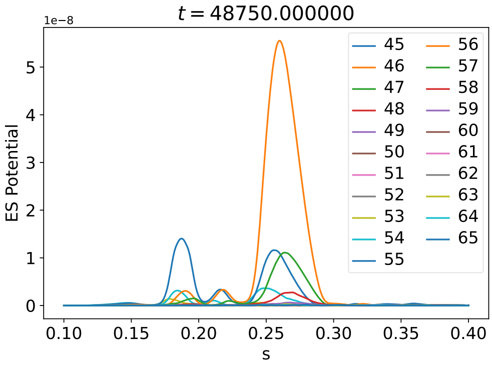
Low frequency: in range $40 < n < 70$ (γ depends on distance between rational and q-extrema)

n=50, frequency: -37.4 kHz
γ/ω = 5.5%



Poloidal harmonics of n=50

[3]Zonca+ 1996; 1998

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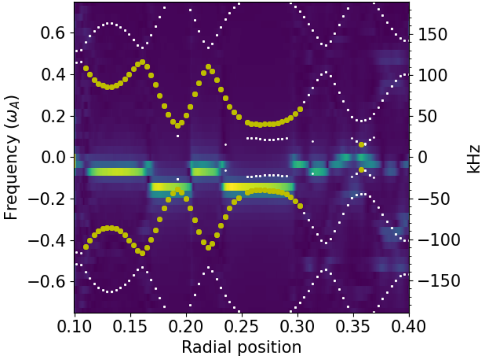

n=50, w/ kinetic spectrum from ligka in white/yellow dots (Im(ω)$< 0, > 0$)

n.b. fig amplitude does not imply mode amplitude

[3] Zonca+ 1996; 1998

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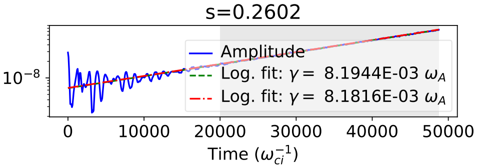
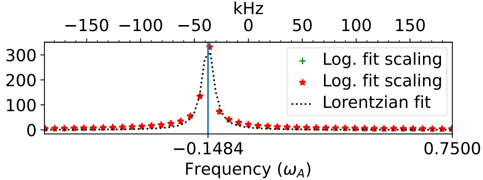




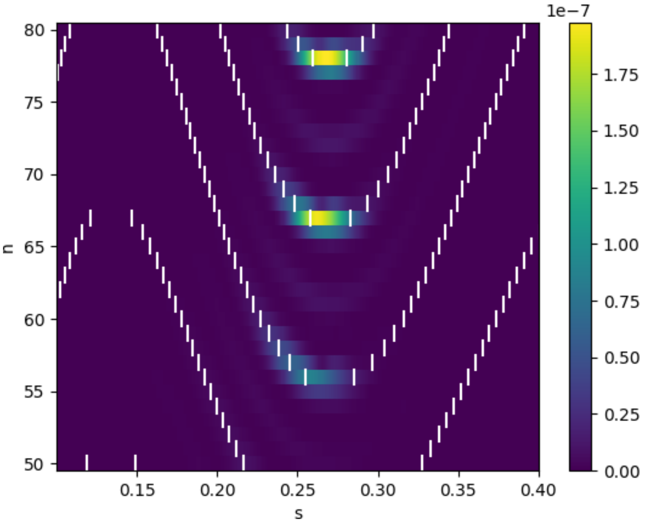
[3]Zonca+ 1996; 1998

ITER PFPO without EPs (meso-n BAEs/AITGs)

Briefly address the q-profile: a q-constrained CHEASE equilibrium run gives a closer match of q(r).

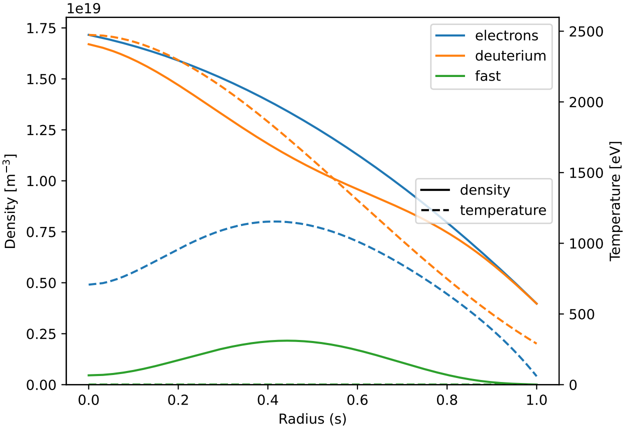
- Δn related to closeness of rational surfaces to extremum of q
- Value Δn comes from rational approximation of q_{max}

(Vertical lines mark rational surfaces)



ASDEX Upgrade #31213 'NLED-AUG'

- Large β_f to β_{total} ratio
- Rich in NL EP physics [Lauber+ IAEA FEC 2018]
  - TAE – EGAM bursts experimentally observed
- Off axis NBI (E_0 = 93 keV)
- Hollow T_e (W impurity)
- Slightly reversed q-profile



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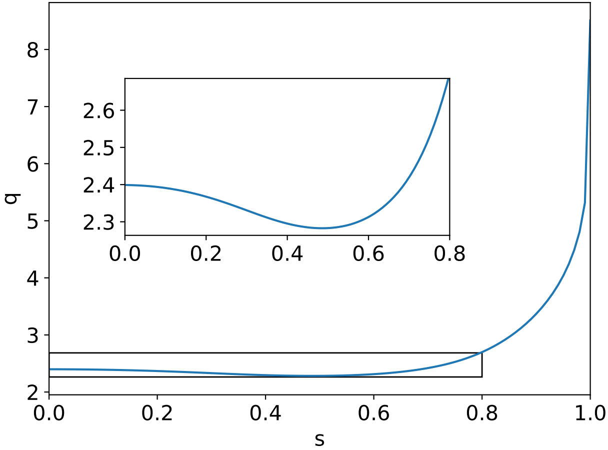
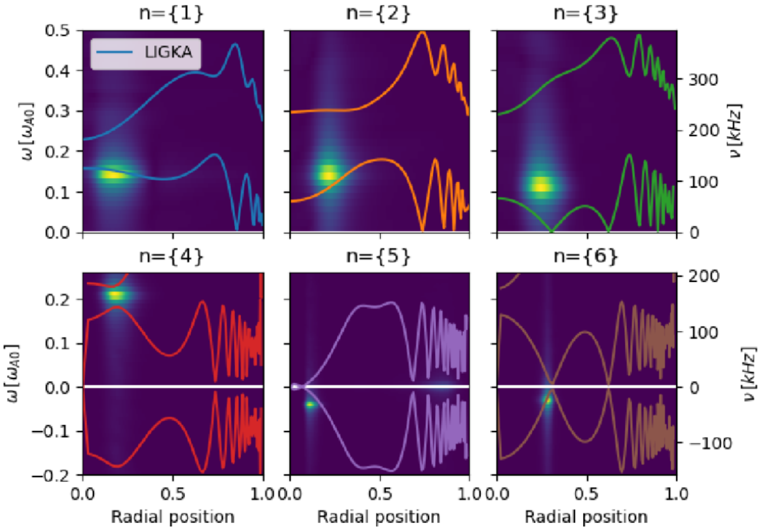


ASDEX Upgrade #31213 'NLED-AUG'

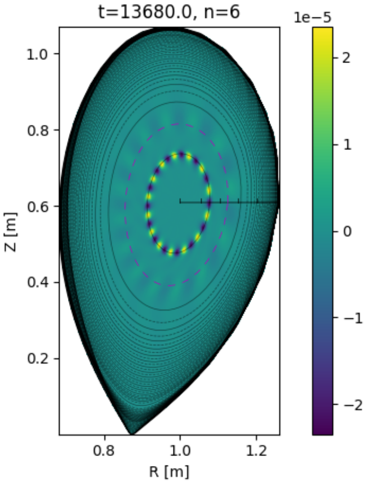
Figure from Vannini+, Varenna 2022 (JPCS, under review)

- Unstable modes for increased *n* driven by bulk plasma



ASDEX Upgrade #31213 ‘NLED-AUG’: n=6

- Narrow mode on the rational surface inside q-min (magenta vertical dashed line)



ASDEX Upgrade #31213 ‘NLED-AUG’: n=6

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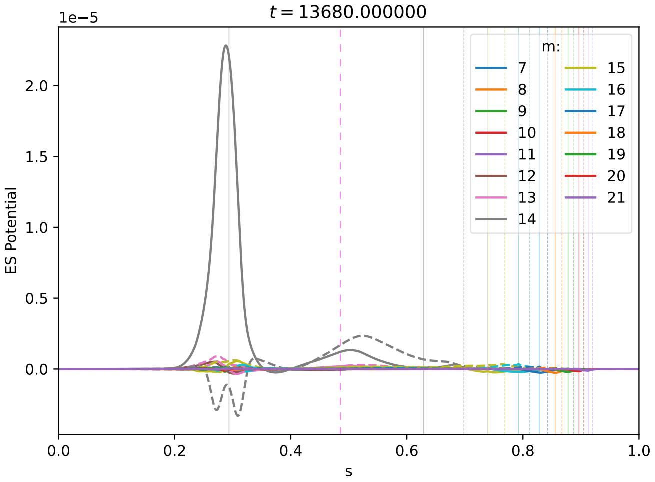
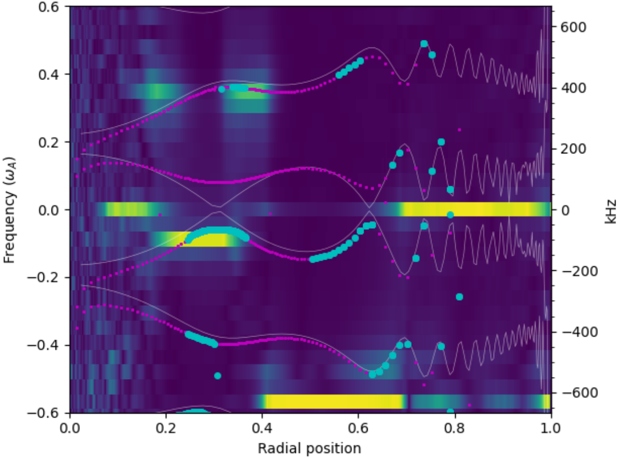


ASDEX Upgrade #31213 ‘NLED-AUG’: n=6

- Narrow mode on the rational surface inside q-min (magenta vertical dashed line)
- Continuum from LIGKA (kinetic: magenta if $\Im(\omega) < 0$, cyan if $\Im(\omega) > 0$)



Summary & Outlook

Summary:

- Kinetic global el.mag. treatment of AEs and EPs applied to ITER PFPO case
  - TAE/EAE/RSAE/BAE in low-n, close to marginal drive with NBI, $n \sim 20$
    - Effect of anisotropic EP distribution to be investigated
  - Unstable AITGs in meso-n (bulk plasma ω^*), $n > 40$
  - Microinstabilities found at large-n (not shown), $n \sim 180$
- Interplay of n=0 (EGAMs) and n>0 (TAE/EPM) studied in ASDEX Upgrade EP scenario
  - Bulk plasma driven low frequency AITG modes driven at $n \geq 5$

Outlook:

- Extend previous global turbulence, AE, & MHD work [Mishchenko; Biancalani; Wang] towards such large plasmas
- Apply more realistic NBI distribution function to ITER NBI [Rettino]