Max-Planck-Institut für Plasmaphysik

Effects of distribution functions in global gyrokinetic simulations of energetic particle driven Alfvénic and EGAM instabilities in ITER and ASDEX Upgrade

Thomas Hayward-Schneider, B. Rettino, A. Bottino, F. Vannini, M. Weiland, Ph. Lauber, A. Mishchenko[1]

Max Planck Institute for Plasma Physics, Garching
[1] *Max Planck Institute for Plasma Physics, Greifswald*

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Outline

Numerical model: the ORB5 Code

Background distribution functions

ASDEX Upgrade “NLED-AUG”

ITER 15MA scenario

ITER PFPO scenario (101006)

ORB5[1]

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

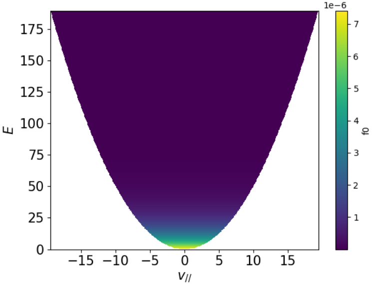
- Filter applied in toroidal and poloidal mode numbers
  - $m(r) = nq(r) \pm \Delta m$
- Effectively mitigates with the so-called cancellation problem using the pullback scheme [Mishchenko 2019]
- These EM results all with kinetic (some w/ reduced mass ratio) electrons, (ES with adiabatic)
- Gyrokinetic or drift-kinetic ions (here: bulk gyro-, EPs drift- kinetic)
- 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

[1] for details, see Lanti+ CPC 2020

Maxwellian

$$F_{0,\mathrm{f},\mathrm{Max.}} = \frac{n_\mathrm{f}(r)}{(2\pi v_\mathrm{th}^2(r))^{3/2}} \exp\left(-E/v_\mathrm{th}^2\right) \exp\left(-\frac{u_\parallel}{2}\left(u_\parallel - 2v_\parallel\right)/\ v_\mathrm{th}^2\right)$$

in absence of shift ($u_\parallel \to 0$), reduces to function of Energy, radius

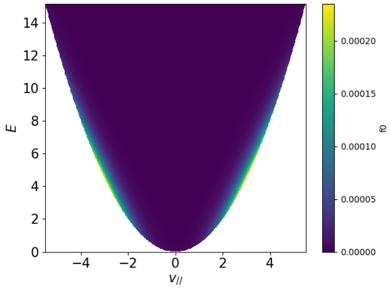


Bump-on-tail[2]

$$F_{0,\mathrm{f},\mathrm{BoT}} = C \cdot n_\mathrm{f}(r) \exp(-E \cdot m_\mathrm{f} / T_\mathrm{f}) \exp(-v_{\|,f}^2/(2T_\mathrm{f})) \cosh(v_\| v_{\|,f} / T_\mathrm{f})$$

function of Energy, radius, $v_\|$

- "Toy" distribution function with strong anisotropy (ideal to study EGAMs)
- Originally zero radial dependence, since extended to include $n(r)$



[2]Original version implemented for [Zarzoso+, NF, 2014], based on GYSELA work

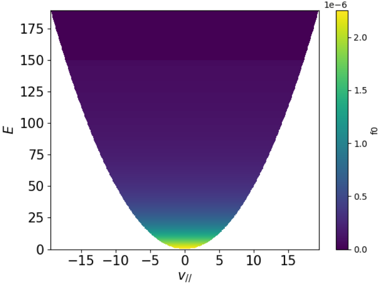
Isotropic Slowing down[3]

$$F_{0,\mathrm{f,SD}} = \frac{3n_\mathrm{f}(r)}{4\pi} \frac{\Theta(v_0 - |v|)}{(v_\mathrm{c}(r)^3 + |v|^3)\ln(1 + v_0/v_\mathrm{c}(r))}$$

also function of Energy ($|v|$), radius

- Decent approximation for alpha particles

Apply to ITER 15MA scenario, previously studied with Maxwellian in [Hayward-Schneider+, NF2021]



[3] Vannini+, thesis+paper 2021+

Anisotropic Slowing down[4]

$$F_{0,\mathrm{f,ASD}} = F_{0,\mathrm{f,SD}}(r, E) \cdot \; C \exp\left(-(\xi - \xi_0)^2/(2\Delta\xi^2)\right)$$

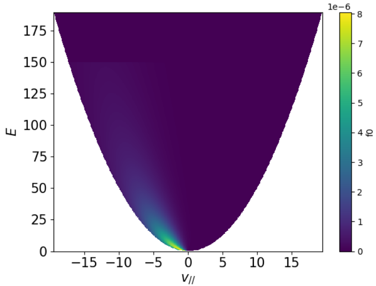
where $\xi = v_{||}/|v|$, $\rightarrow$ function of Energy, radius, and parallel velocity

Semi-analytical: F_0 analytic, but compute $\partial F_0/\partial X$ numerically

- Reasonable (parameterizable) approximation for NBI

Apply to NBI driven AEs and EGAMs in ASDEX Upgrade

Apply to NBI driven AEs in ITER PFPO



[4] Rettino+, paper 2021+

Numerical F0

In principle, arbitrary function $F_0(r, v_{||}, E)$ also now treated fully numerically in ORB5.

We "**just**" require F_0 on a mesh.

- To date, we can read in one of the previous analytical expressions, but also coupled to RABBIT.
- Work ongoing to couple to, e.g. ASTRA NBI module via IMAS

RABBIT

- RABBIT [Weiland+, NF, 2018+19]
  - real-time capable NBI code
- Describes NBI distribution function in experiment
- Non-Monte-Carlo method gives smooth function, good for derivatives
- We use RABBIT for ASDEX Upgrade (AUG) NBI F_0 (e.g. shot #31213 (NLED-AUG)) in the time-independent mode
- Coordinate mapping performed between RABBIT and ORB5

$$f_{-}(|v|, \xi) = \frac{1}{2\pi} \frac{\tau_s}{v^3 + v_{\mathrm{c}}^3} \cdot \sum_{l=0}^{\infty} \left(l + \frac{1}{2} \right) P_l(\xi) S_l \cdot \left(\frac{v_0^3 + v_{\mathrm{c}}^3}{v^3 + v_{\mathrm{c}}^3} \frac{v^3}{v_0^3} \right)^{\frac{\beta}{3} l(l+1)}$$

$$\xi = v_{\|} / v$$

“NLED-AUG”: ASDEX Upgrade #31213[5]

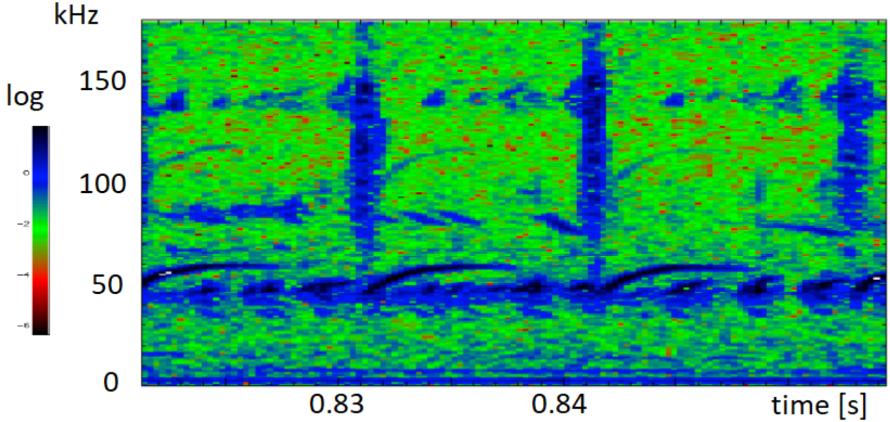
ASDEX Upgrade case with large EP to bulk plasma β ratio

- Off-axis NBI, NBI angle scan performed
- Bursts of TAEs/EPMs and EGAMs observed
- Previous works [Novikau, Di Siena, Vannini, Vlad, ...] modelled this case
  - EGAMs (bump on tail), TAE/EPM (Maxwellian), interaction of EGAMs & EPMs (bump on tail)
- Starting to become more realistic:
  - TAE/EPM with isotropic slowing down
  - EGAM with anisotropic slowing down
  - EGAM with RABBIT NBI

[5] Lauber+, IAEA FEC 2018

“NLED-AUG”: ASDEX Upgrade #31213

TAE → EGAM bursts observed in experiment



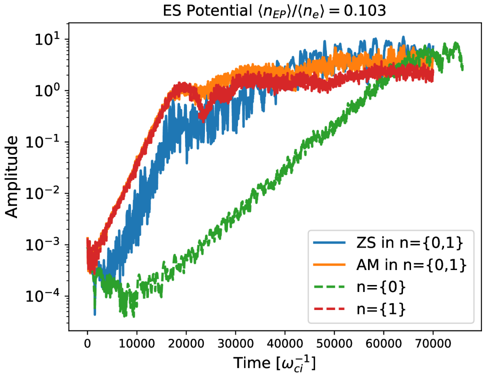
"NLED-AUG": Results

Interaction of EPM & EGAM[6]

n=0 & n=1 different from n=[0,1]

- High EP density, $n = 0$ enhanced
- Low EP density, $n = 1$ enhanced

n=1 mode also studied with isotropic slowing down[7]



high-EP density

[6] Details in Vannini+ PoP 2021

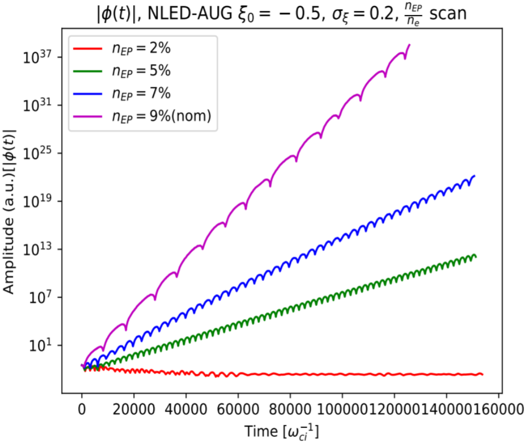
[7] Vannini+ 2021+

"NLED-AUG": Results

Study with ES Simulations of n=0 EGAM[8]

- Anisotropic slowing down
- RABBIT NBI distribution[8]

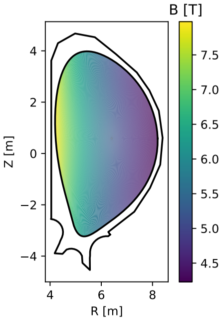
EM simulations with n=1 EPM also underway



Anisotropic slowing down driven EGAM

[8] Rettino+ 2021+

ITER 15 MA Scenario[9]



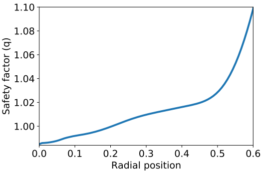
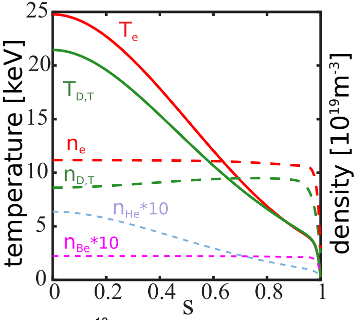
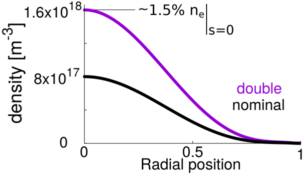


Fig. Lauber 2015





[9] Polevoi+ 2002; ITPA; similar to IMAS #131018 (slightly different q-profile)

Simplifying the problem

- Remove density/temperature pedestal gradients
- Fast ions: 3.5MeV **Slowing down** & 900keV Maxwellian
- Neglect impurity species (He, Be)
- Hybrid isotope: 50% ^{2}D + 50% ^{3}T $\rightarrow$ 100% $^{2.5}$DT
- Increase electron mass: m_i/m_e: 4550 $\rightarrow$ 200
- Neglect gyroaverage in fast ions
- Double EP density

All the isotope effects & m_{e} studied separately, not reported here

Summary of previous results

Summary of Hayward-Schneider+ NF 2021, EPPI 2019, ...

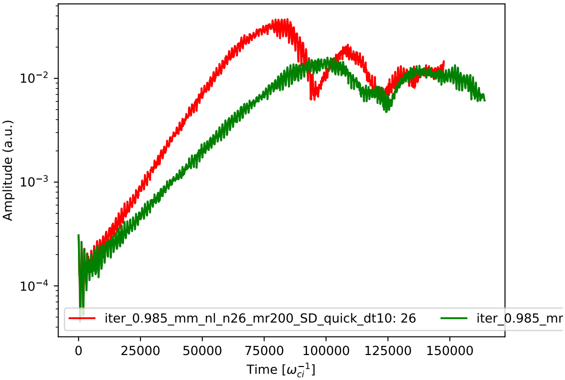
- low-n (e.g. 12) TAEs have radially global mode structures
- w/o EP FLR, γ peak around $n = 30$
- w/ EP FLR, γ for $n > 20$ reduced $\rightarrow$ peak $20 < n < 25$
- Single modes cause negligible EP redistribution
- Multi (e.g. $[20 \ldots 30]$) modes cause significant EP redistribution[10]
  - Subdominant edge TAEs nonlinear dominant
- Effects of Zonal physics as-yet unstudied

[10] At double EP density

Slowing down

Replacing 900 keV Maxwellian with more realistic 3.5 MeV isotropic slowing down

TAE drive increased



(low resolution runs)

Slowing down

n=26

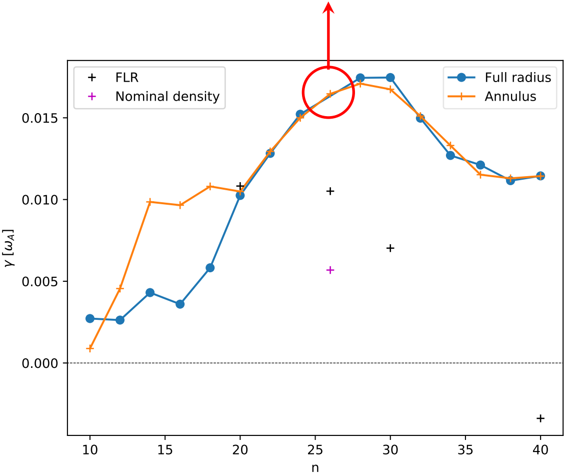
$\gamma = 0.0218\ \omega_{\mathrm{A}}$

(high resolution run)

c.f. $\approx 0.016\ \omega_{\mathrm{A}}$ for Maxwellian

Previous Maxwellian underestimated growth rate.

Next: realistic distribution $\rightarrow$ nominal density + EP FLR

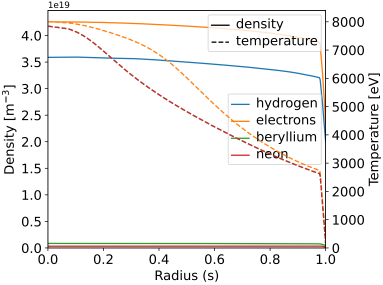


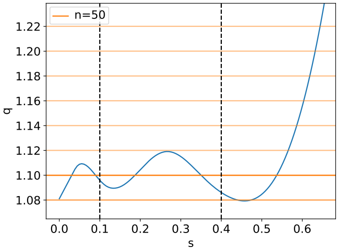
Black: with EP FLR (bulk ion FLR always kept)

ITER PFPO Scenario (IMAS: 101006#50)[11]

Pre-fusion-power-operation (PFPO).
Half current.
Half field.
ITER wants to know:

- Will (NBI) EPs drive AEs unstable?
- If so: enough EP transport to need to take action?





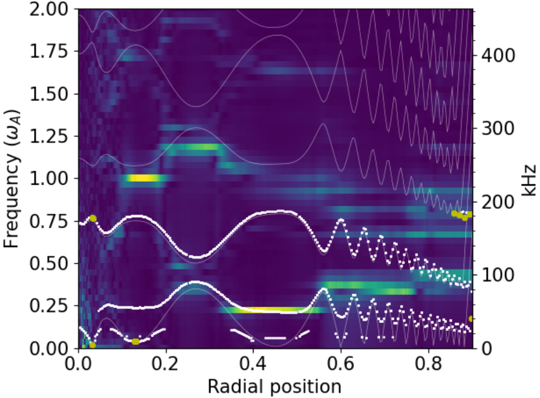
[11] Polevoi+ 2021; ITPA B.11.12

ITER PFPO without EPs

Preliminary results

ITER PFPO without EPs

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



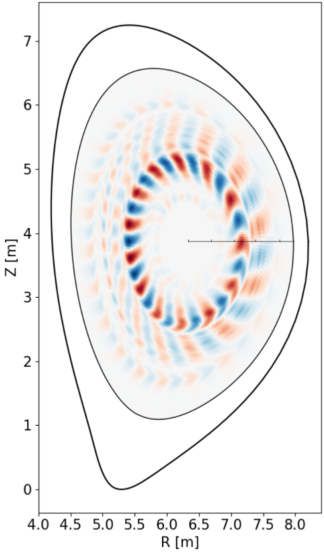
n=12

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)

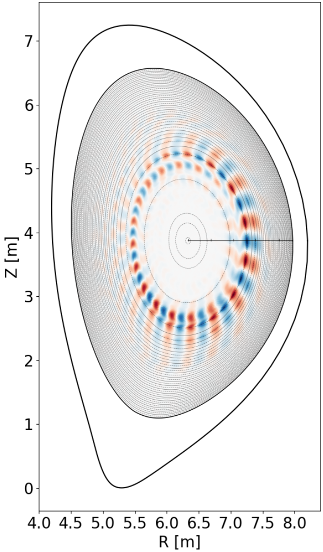
n=12



ITER PFPO without EPs

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

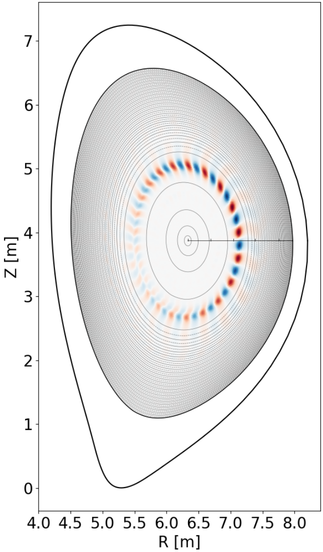
n=16



ITER PFPO without EPs

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

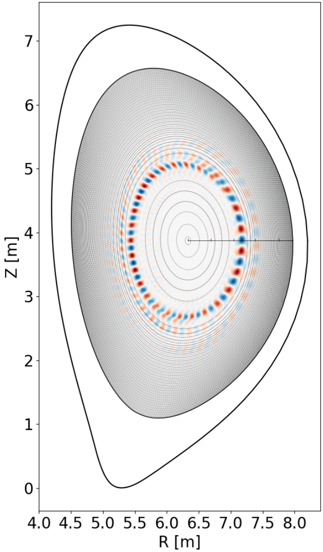
n=20



ITER PFPO without EPs

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

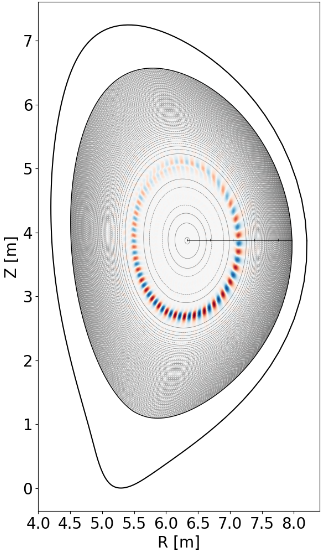
n=26



ITER PFPO without EPs

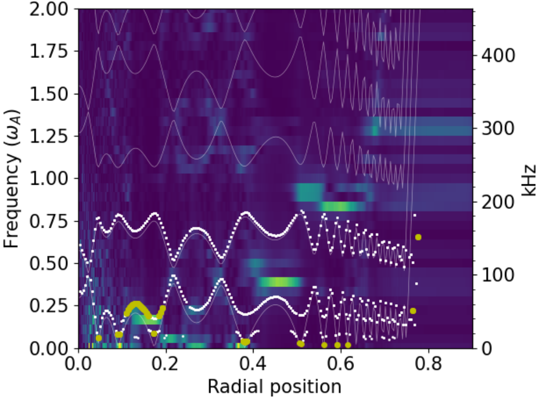
AEs in the absence of EPs
(stable, weakly damped)
TAEs, EAEs, lower frequency
(RSAE and/or BAE)

n=32



ITER PFPO without EPs

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



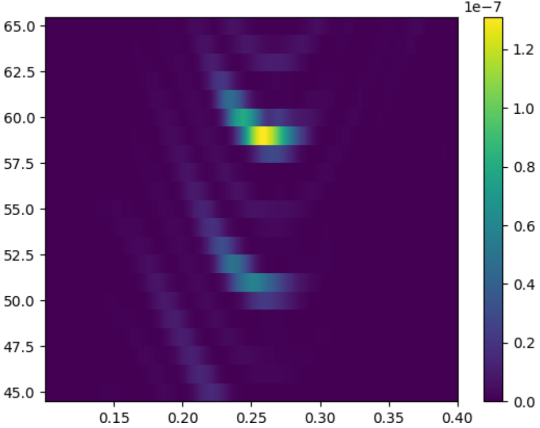
n=32

Alfvén continuum from ligka (thick: kinetic)

Now ready for NBI data from
ITER/IMAS

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

Higher-n core BAEs/AITGs in the absence of EPs (driven **unstable** by **bulk** plasma[12])
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

[12] Zonca+ 1996; 1998

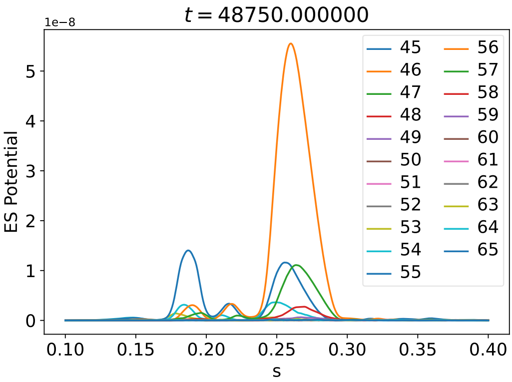
ITER PFPO without EPs (meso-n BAEs/AITGs)

Higher-n core BAEs/AITGs in the absence of EPs (driven **unstable** by **bulk** plasma[12])

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

n=50, frequency: -37.4 kHz

$\gamma/\omega = 5.5\%$



Poloidal harmonics of n=50

[12] Zonca+ 1996; 1998

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

Higher-n core BAEs/AITGs in the absence of EPs (driven **unstable** by **bulk** plasma[12])

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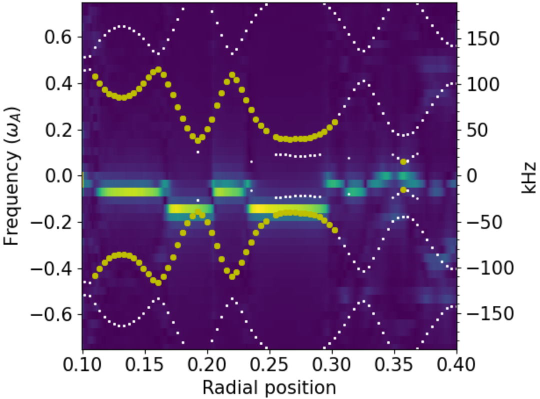


n=50, w/ kinetic spectrum from ligka in white/yellow dots (Im(ω)< 0, > 0)

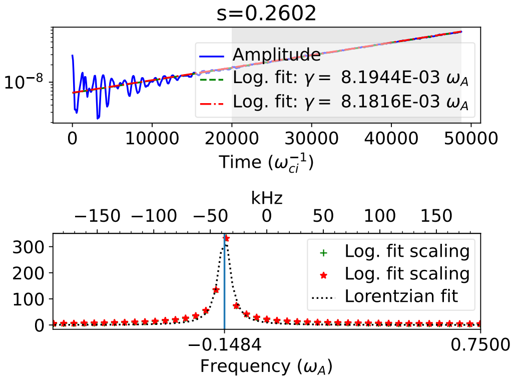
n.b. fig amplitude does not imply mode amplitude

[12]Zonca+ 1996; 1998

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

Higher-n core BAEs/AITGs in the absence of EPs (driven **unstable** by **bulk** plasma[12])

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



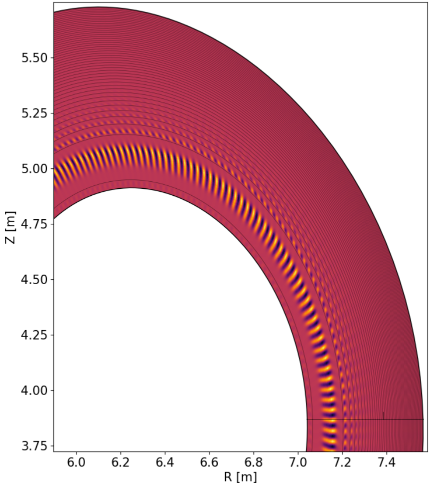
n=50, frequency: -37.4 kHz

$\gamma/\omega = 5.5\%$

[12] Zonca+ 1996; 1998

ITER PFPO without EPs (linear microturbulence)

- Search high n (100–480)
- Found instability near q-min ($s \approx 0.45$)
- Electromagnetic simulations
- Peak growth n∼150-200



n=180, δn_{e}

Summary

Numerics:

- Distribution functions added to ORB5
- Coupled to NBI code RABBIT

ASDEX Upgrade #31213:

- n=0 enhanced in coupled simulation – qual. similar to experiment
- EGAM & TAE/EPM with realistic NBI F_0 started

ITER 15MA Scenario

- 3.5 MeV slowing down: $\gamma \uparrow$
- Nominal study underway

ITER PFPO (101006)

- Multi scale problem
  - (Stable) TAE/EAE/RSAE/BAE in low-n (ready to add 1 MeV NBI)
  - Unstable BAEs in meso-n (bulk plasma ω^*)
  - High-n linear turbulent instabilities found