MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Global gyrokinetic instabilities going to high plasma beta

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and the ORB5 and EUROfusion TSVV10 and ATEP Teams

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Outline

Background – Electromagnetic turbulence

The ORB5 global gyrokinetic code

ITER 7.5MA scenario
- Damped Alfvén eigenmodes
- Microscale modes
- Unexpected "mesoscale" modes – "AITGs"

JET and AUG cases
- Return of the AITGs

ITG/AITG/KBM in simple tokamak geometry
- Effect of energetic particle beta
- Nonlinear AITG properties

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- Local **&** electrostatic turbulence well studied
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- Global & electromagnetic energetic particle (Alfvén eigenmodes) physics well studied
- "Electromagnetic stabilization" and "Energetic particle (fast ion)" stabilization of turbulence increasingly discussed
    - Physical explanations seem to be unclear (competing?), also hard to say what is consequence of model used
    - Hard to decorrelate from MHD physics

Goals of this talk

- Take a step back, try to understand global electromagnetic instabilities, especially in a linear picture
- Maybe lead to you question some things you think you know about the electrostatic Ion Temperature Gradient (ITG) to electromagnetic Kinetic Ballooning Mode (KBM) transition

Background – Electromagnetic turbulence

For example, [Goerler+ PoP (2016)]

- benchmark of European gyrokinetic codes, global extension of the cyclone-benchmark-case (CBC)

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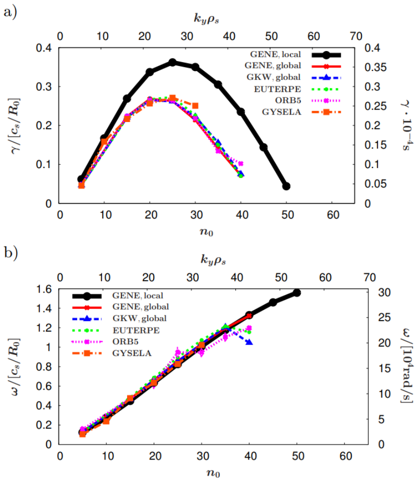

Goerler+ PoP

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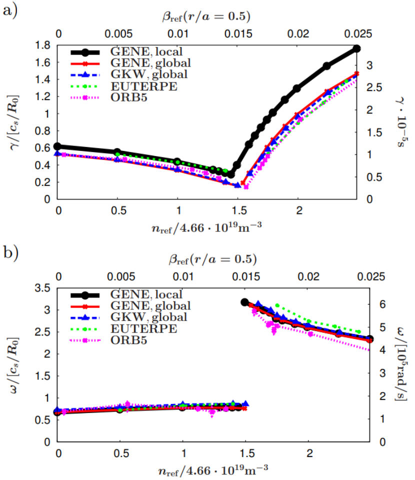
- Scan vs beta at fixed mode number (n=19)



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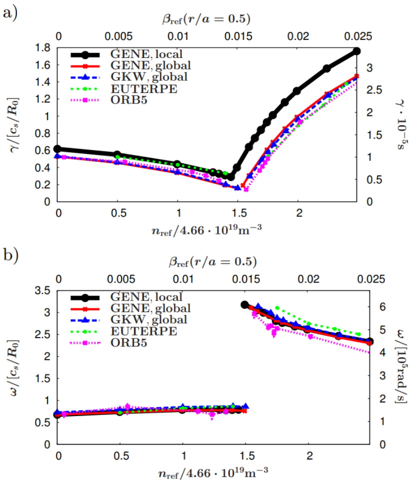
In *my* opinion, this is the “ITG-KBM” picture that most people have in their mind



Goerler+ PoP

Global electromagnetic gyrokinetic code ORB5

ORB5 [1] (and EUTERPE)

"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]
- Here: gyrokinetic ions, drift-kinetic electrons
- 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, Mishchenko+ CPC 2019

ORB5 particle equations in mixed variables

$$\dot{\mathbf{R}}^{(0)} = v_{\|}\mathbf{b} - {v_{\|}}^2 \frac{cm_\mathrm{s}}{qB_{\|}^*}\mathbf{G} + \mu \frac{Bcm_\mathrm{s}}{qB_{\|}^*}\mathbf{b} \times \frac{\nabla B}{B}$$

$$\dot{\mathbf{R}}^{(1)} = \frac{\mathbf{b}}{B_{\|}^*} \times \nabla \left\langle \phi - v_{\|}{A_{\|}}^s - v_{\|}{A_{\|}}^h \right\rangle - \frac{q_\mathrm{s}}{m_\mathrm{s}} \left\langle {A_{\|}}^h \right\rangle \mathbf{b}^*$$

$$\dot{v_{\|}}^{(0)} = \mu B \nabla \cdot \mathbf{b} + \mu v_{\|} \frac{cm_\mathrm{s}}{qB_{\|}^*}\mathbf{G} \cdot \nabla B$$

$$\dot{v_{\|}}^{(1)} = -\frac{q_\mathrm{s}}{m_\mathrm{s}} \left[\mathbf{b}^* \cdot \nabla \left\langle \phi - v_{\|}{A_{\|}}^h \right\rangle + \frac{\partial}{\partial t} \left\langle {A_{\|}}^s \right\rangle \right] - \mu \frac{\mathbf{b} \times \nabla B}{B_{\|}^*} \cdot \nabla \left\langle {A_{\|}}^s \right\rangle$$

$$\dot{\epsilon}^{(1)} = v_{\|}\dot{v_{\|}}^{(1)} + \mu \nabla B \cdot \dot{\mathbf{R}}^{(1)}$$

ORB5 field equations in mixed variables

Gyrokinetic quasineutrality (poisson) equation:

$$-\nabla \cdot \left[\left(\sum_s \frac{q_{\mathrm{s}}^2 n_{\mathrm{s}}}{T_{\mathrm{s}}} \rho_{\mathrm{s}}^2 \right) \nabla_\perp \phi \right] = \sum_s q_{\mathrm{s}} n_{1\mathrm{s}}$$

Splitting of parallel Ampère's law:

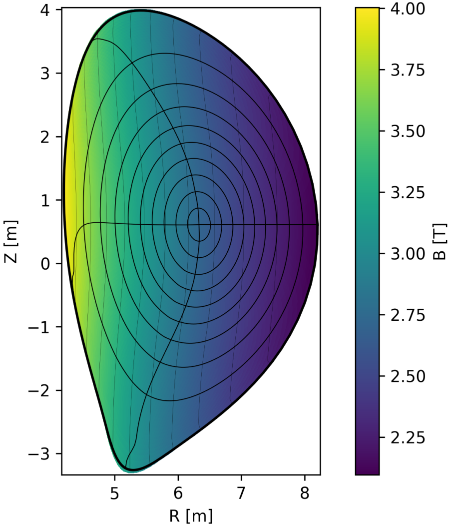
$$\frac{\partial}{\partial t} {A_\parallel}^s + \mathbf{b} \cdot \nabla \phi = 0$$

$$\left(\sum_s \frac{\beta_{\mathrm{s}}}{\rho_{\mathrm{s}}^2} - \nabla_\perp^2 \right) {A_\parallel}^h = \mu \sum_s j_{\parallel 1\mathrm{s}} + \nabla_\perp^2 {A_\parallel}^s$$

ITER 7.5MA Pre-fusion scenario

ITER 7.5MA (IMAS #101006) Pre-fusion-power-operation-2 case

- H-plasma, 1/2 fields, 1/2 current, NBI-heated
- Low shear, (multi-) reversed q-profile due to off-axis beams
- Flat density, peaked temperature profiles



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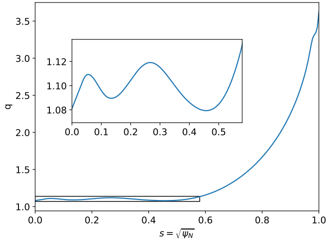
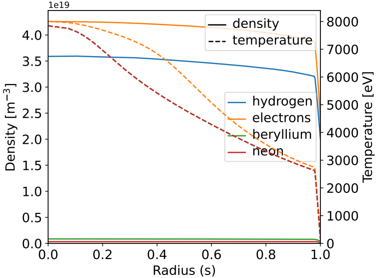
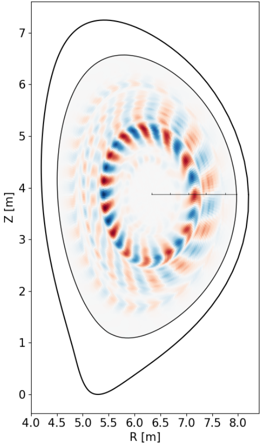




ITER 7.5MA without EPs

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

n=12 (BAE)



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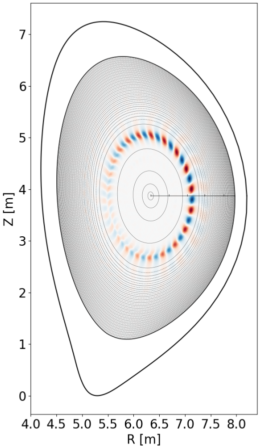
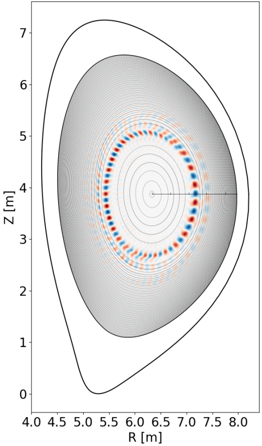


ITER 7.5MA without EPs

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

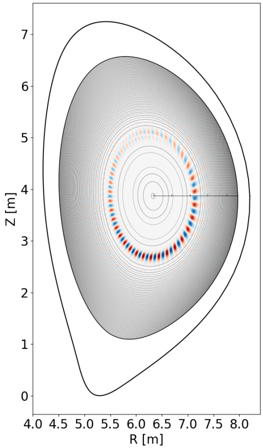
n=26 (EAE)



ITER 7.5MA without EPs

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

n=32 (RSAE)



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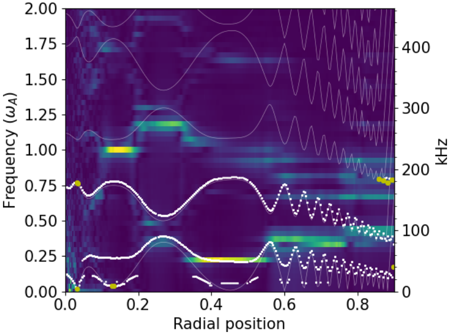
n=12 (BAE)



n=12

Alfvén continuum from ligka (thick: kinetic)

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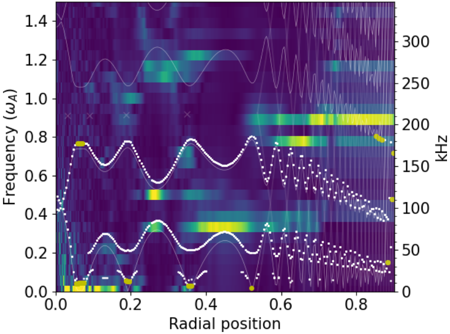

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Alfvén continuum from ligka (thick: kinetic)

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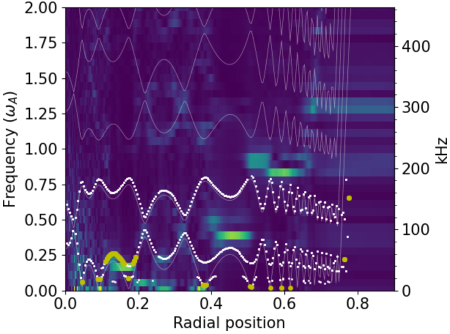


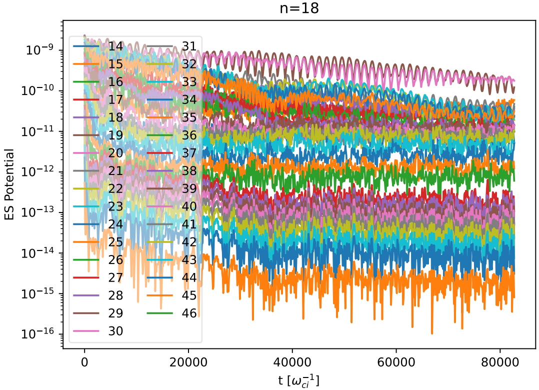
n=32

Alfvén continuum from ligka (thick: kinetic)

ITER 7.5MA with EPs

Adding EP distribution,
introduce AE drive

E.g. n=18



Nominal EP density not enough to drive AEs

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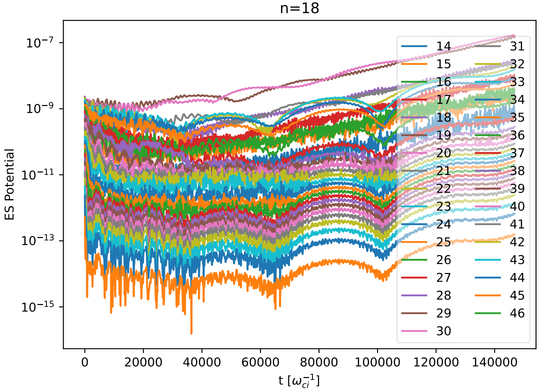

2x n_{EP}, growing beating mode(s)

ITER 7.5MA with EPs

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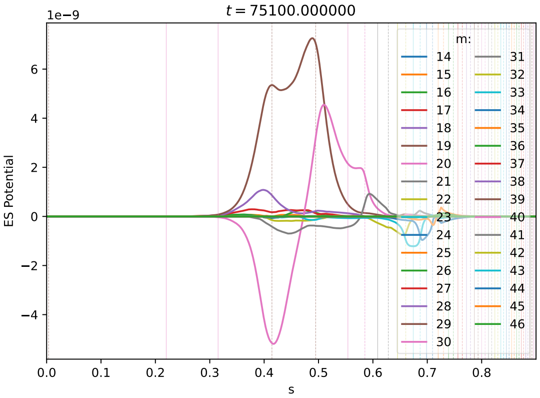

2x n_{EP}, twin TAE locations at $s \sim [0.414, 0.495]$

ITER 7.5MA with EPs

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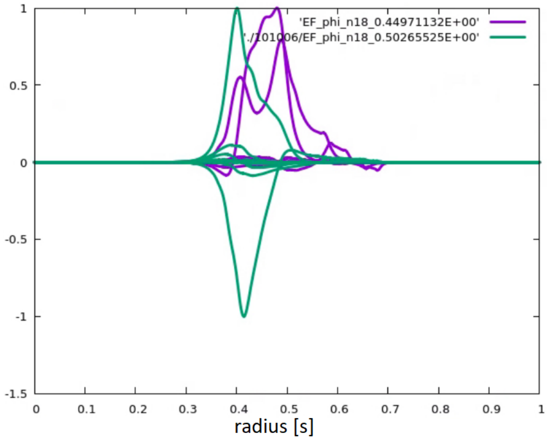

Twin TAEs found by LIGKA, mixed parity

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Adding EP distribution,
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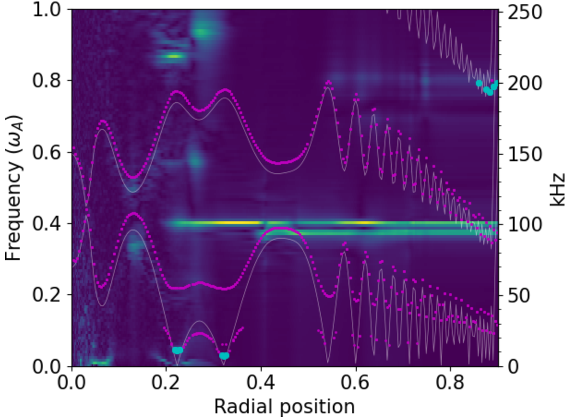

2x n_{EP} (n.b. Continuum mismatch: q_{LIGKA} vs q_{ORB5})

ITER 7.5MA (without EPs)

Increasing the mode number, looking for other kinds of instabilities

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- ITG – Unstable electrostatc modes found in range of $n \approx 180 - 200$

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- Unexpected electromagnetic modes found in range of *n* $\approx 50 - 80$

ITER 7.5MA (without EPs)

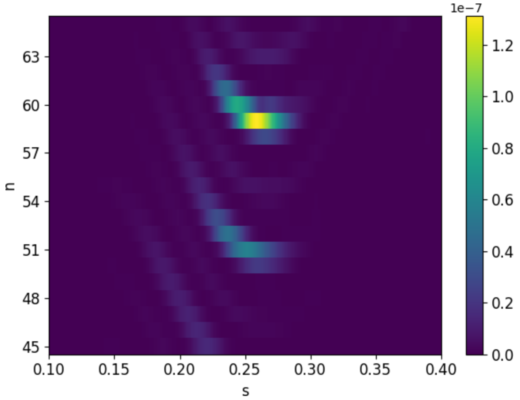
Increasing the mode number, looking for other kinds of instabilities

- ITG – Unstable electrostatc modes found in range of $n \approx 180 - 200$
- Unexpected electromagnetic modes found in range of $n \approx 50 - 80$
    - Alfvénic Ion Temperature Gradient modes (AITG)

ITER 7.5MA without EPs (meso-n BAEs/AITGs)

Higher-n core BAEs/AITGs (Alfvénic ITG) in the absence of EPs (driven **unstable** by **bulk** plasma[2])
– flute-like structure

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

[2] Zonca+ 1996; 1998

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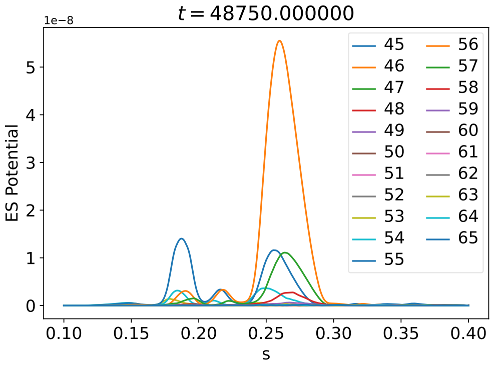
n=50, frequency: -37.4 kHz
γ/ω = 5.5%



Poloidal harmonics of n=50

[2] Zonca+ 1996; 1998

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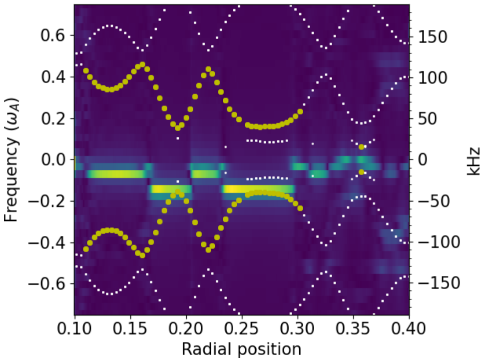

n=50, w/ kinetic spectrum from ligka in white/yellow dots (Im(ω)$< 0, > 0$)

n.b. fig amplitude does not imply mode amplitude

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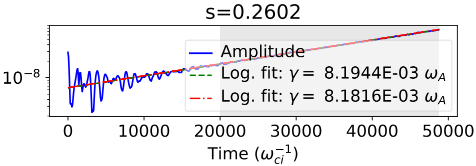

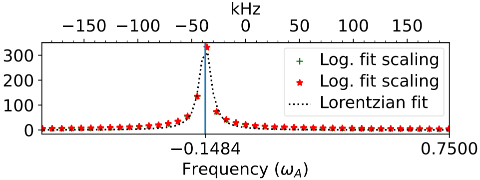

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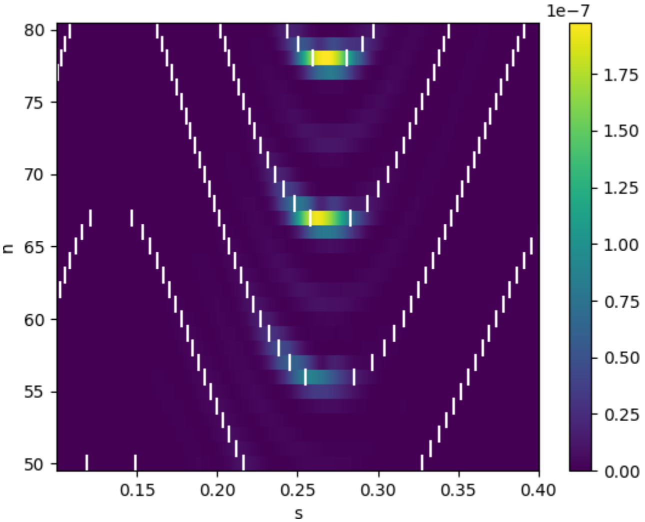
ITER 7.5MA without EPs (meso-n BAEs/AITGs)

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)

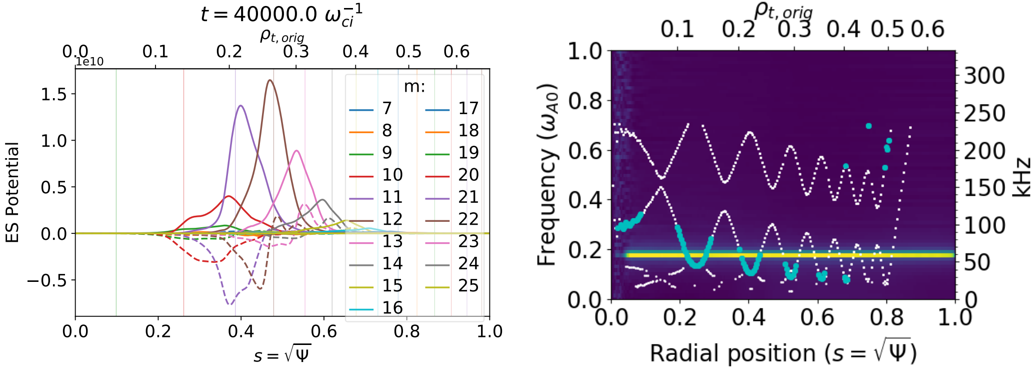


JET & AUG

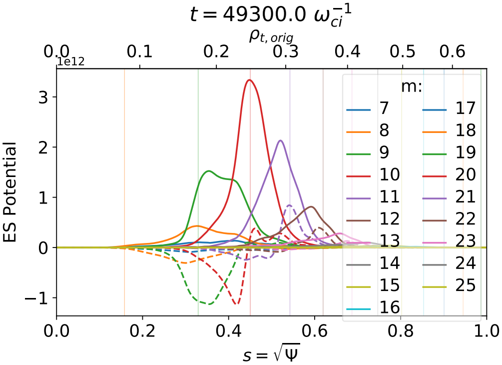
JET #73224

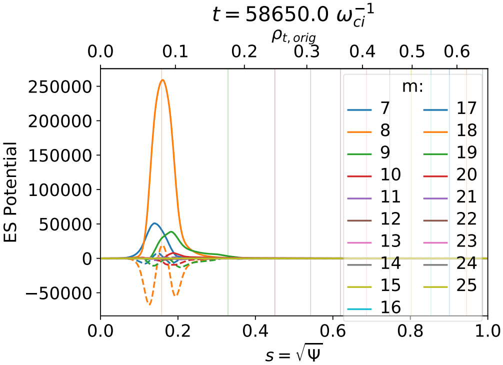
- In [Di Siena, Hayward-Schneider, et al., NF (2023)], investigation into EM EP-driven modes in the plasma core
- JET #73224 case chosen, density rescaled to increase beta
  - Monotonic q-profile
- Comparison between GENE local, GENE global, ORB5 global
  - LIGKA Alfvén continuum results included for comparison to reach physics explanation
- Even without EPs, Alfvénic mode weakly unstable
  - LIGKA found $\Im(\omega) > 0$ in Alfvén continuum, ω^* pushing AITG unstable

JET #73224 n=7 w/ EPs



JET #73224 n=6 w/ & w/o EPs

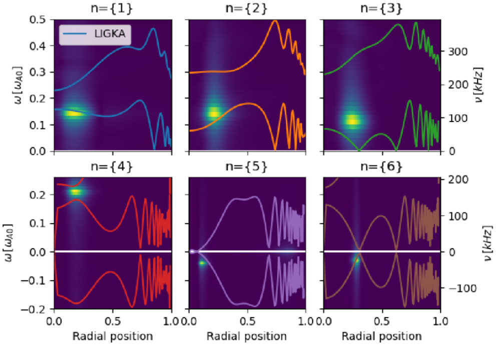




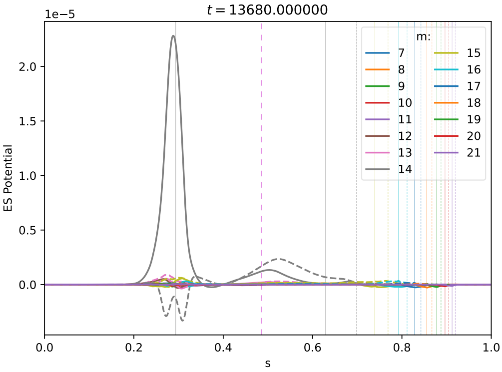
44 kHz / 57 kHz

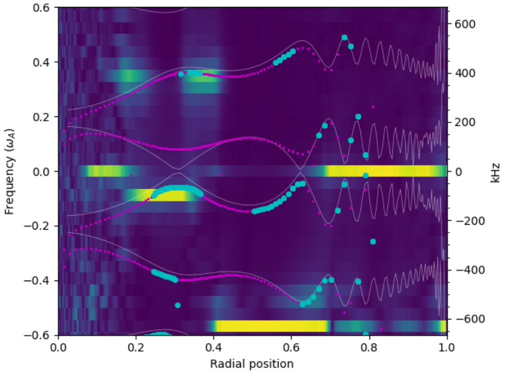
AUG #31213

- ASDEX Upgrade shot #31213, aka “NLED” case
- Shot with rich nonlinear EP physics, due to large $\beta_{\mathrm{EP}}/\beta_{\mathrm{th}}$ ratio
- Main physics considered, $n = 0$, $n = 1$, and their interaction
- In [Vannini, ..., Hayward-Schneider, et al., JPCS (2022)] *en passant*, electromagnetic $n = 6$ mode found to be unstable; driven by bulk plasma



AUG #31213 n=6

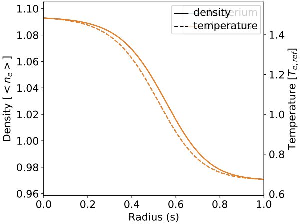


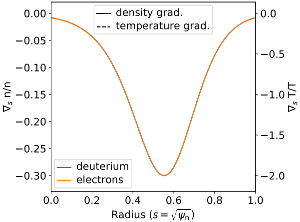


97 kHz

Simplified geometry

Scenario[3]





Hydrogen plasma

$T(0) = 4.4\,\mathrm{keV}$

$n(0) = 9.478 \times 10^{17}\,\mathrm{m}^{-3}$

$B = 1\,\mathrm{T}$

$R0 = 10\,\mathrm{m}$

$a = 1\,\mathrm{m}$

$\bar{q} = 1.1 + 0.8\frac{r}{a}^2$

$\rho_*(s = 0.5) = 1/180$

$m_\mathrm{e}/m_\mathrm{i} = 1/200$

$\kappa_{n,i} = 0.3$ (a/Lx)

Scenario[4]

Hydrogen plasma

$T(0) = 4.4\,\mathrm{keV}$

$n(0) = 9.478 \times 10^{17}\,\mathrm{m}^{-3}$

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$R0 = 10\,\mathrm{m}$

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$\bar{q} = 1.1 + 0.8\frac{r}{a}^2$

$\rho_*(s = 0.5) = 1/180$

$m_\mathrm{e}/m_\mathrm{i} = 1/200$

$\kappa_{n,i} = 0.3$ (a/Lx)

$\kappa_{T,i} = 2.0$

$\kappa_{T,e} = 2.0$

EPs (when present):

$T_\mathrm{f}/T_\mathrm{e} = 10$

$< n_\mathrm{f} > / < n_\mathrm{e} >= \mathrm{scan}$ (1%, 2%, 5%, 10%)

$\kappa_{n,f} = 0.3$

$\kappa_{T,f} = [0.0, 2.0]$

[4] PPCF 64 (2022) 104009 A Mishchenko et al.

Scenario[4]

Hydrogen plasma
$T(0) = 4.4\,\mathrm{keV}$
$n(0) = 9.478 \times 10^{17}\,\mathrm{m}^{-3}$
$B = 1\,\mathrm{T}$
$R0 = 10\,\mathrm{m}$
$a = 1\,\mathrm{m}$
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$\rho_*(s = 0.5) = 1/180$
$m_\mathrm{e}/m_\mathrm{i} = 1/200$
$\kappa_{n,i} = 0.3$ (a/Lx)
$\kappa_{T,i} = 2.0$
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$T_\mathrm{f}/T_\mathrm{e} = 10$
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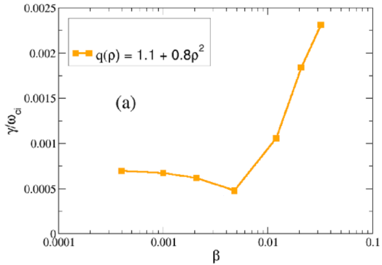
$\kappa_{T,f} = [0.0, 2.0]$

Play with thermal beta, and EP beta to understand physics

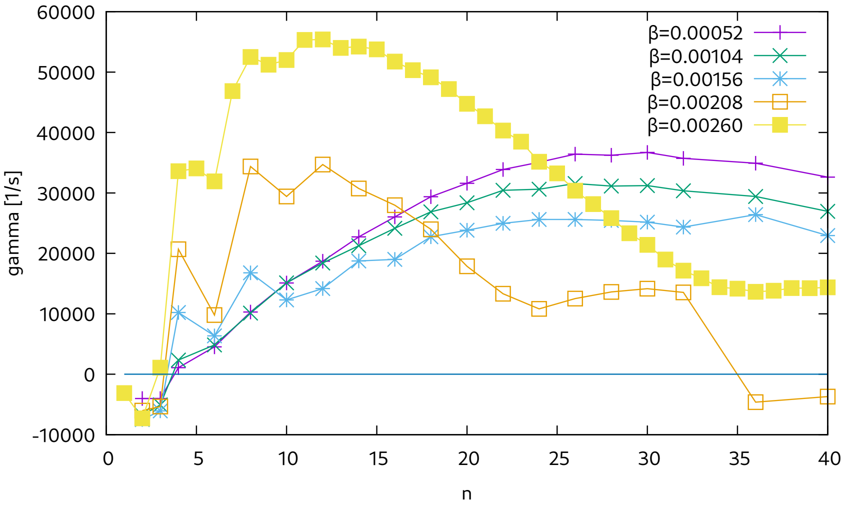
[4] PPCF 64 (2022) 104009 A Mishchenko et al.

Background (Alexey)

- Alexey studied this case in paper last year, “ITG-KBM” transition with increasing β
- Here showing integral over all modes during linear phase of NL simulations
- My goal is to study the linear phase in detail

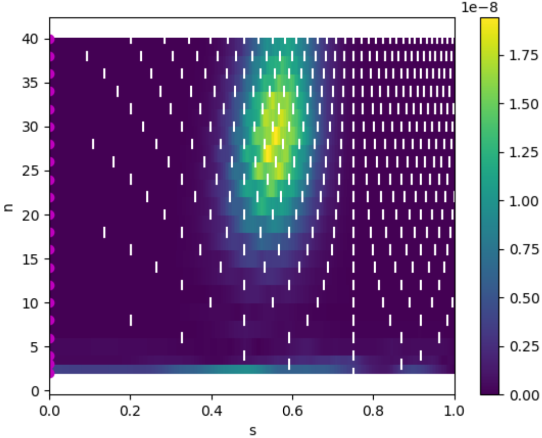


β scan



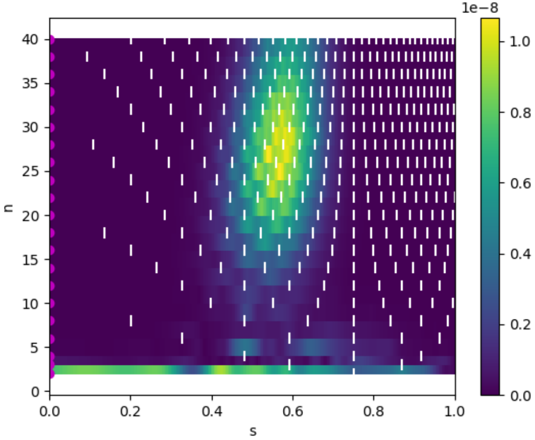
β=0.00052
β=0.00104
β=0.00156
β=0.00208
β=0.00260
gamma [1/s]
60000
50000
40000
30000
20000
10000
0
-10000
0
5
10
15
20
25
30
35
40
n

Rational Surfaces



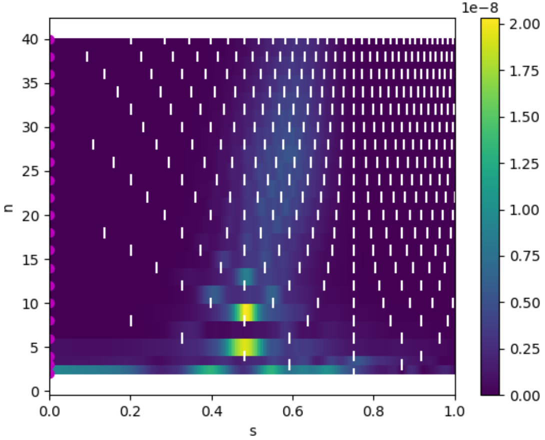
$$\beta_{\mathrm{e,ORB5}} = 0.00052$$

Rational Surfaces



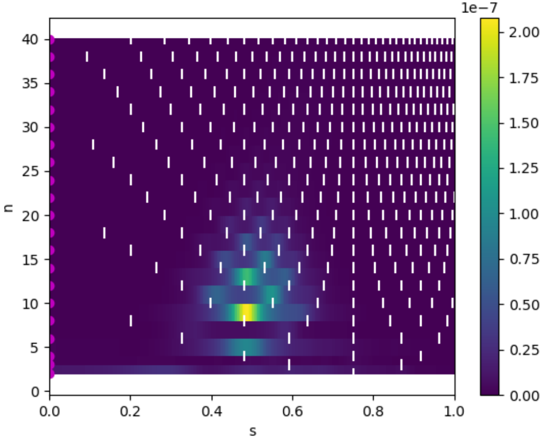
$\beta_{\mathrm{e,ORB5}} = 0.00104$

Rational Surfaces



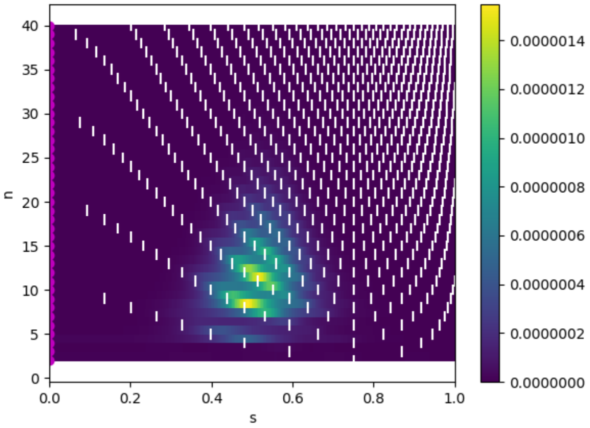
$\beta_{\mathrm{e,ORB5}} = 0.00156$

Rational Surfaces



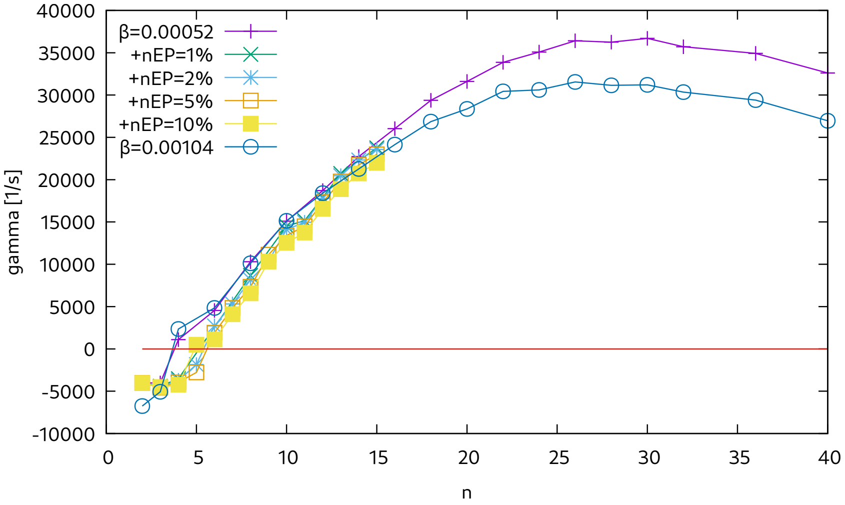
$\beta_{\mathrm{e,ORB5}} = 0.00208$

Rational Surfaces

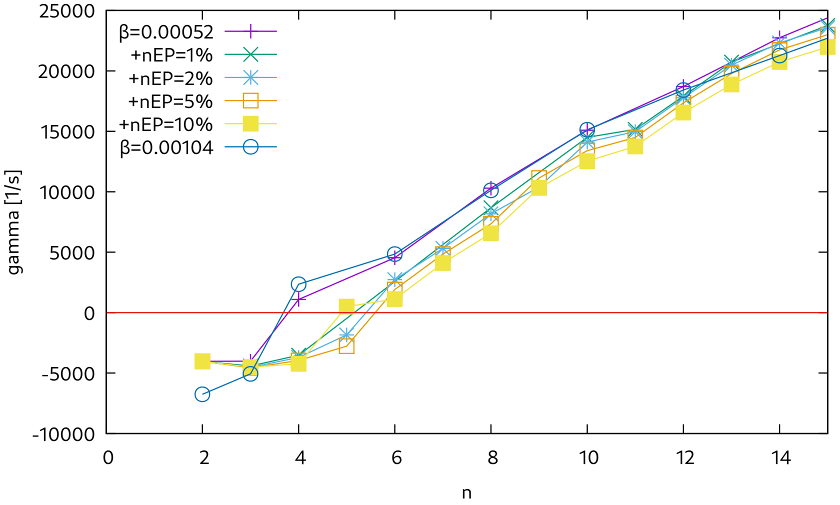


$$\beta_{\mathrm{e,ORB5}} = 0.00260$$

EP scan ($\kappa_{T,f} = 2.$)



EP scan ($\kappa_{T,f} = 2.$)

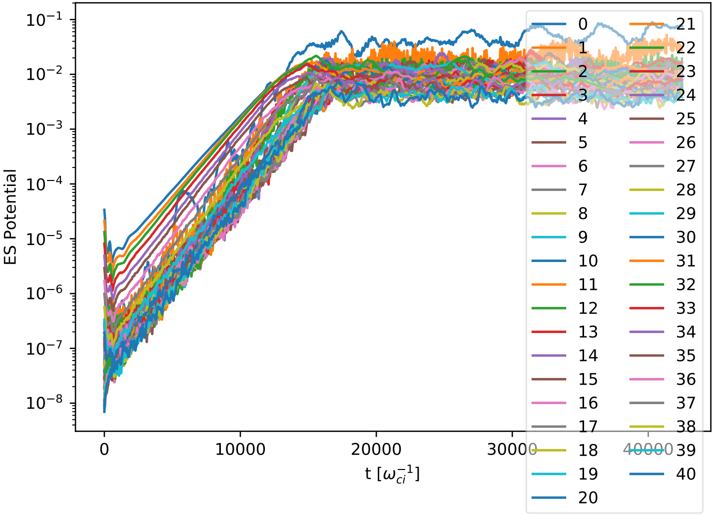


Nonlinear scan

Running multi-n (0-40) runs, like [Mishchenko+ 2023]

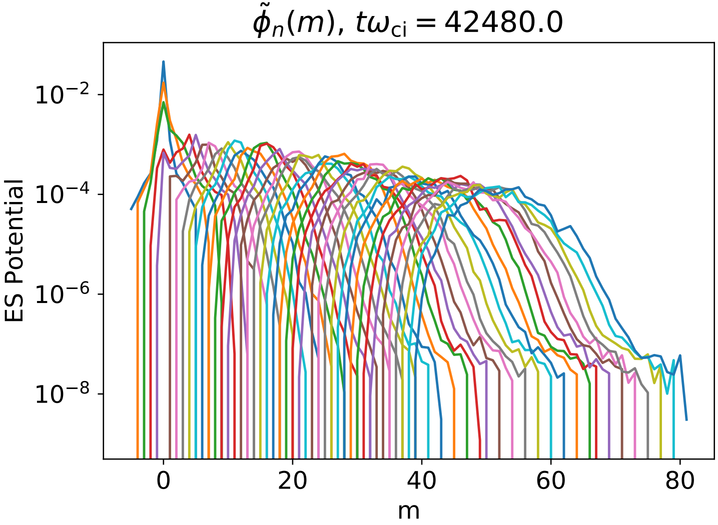
Nonlinear scan

Low beta ($\beta_\mathrm{e} = 0.0005$)



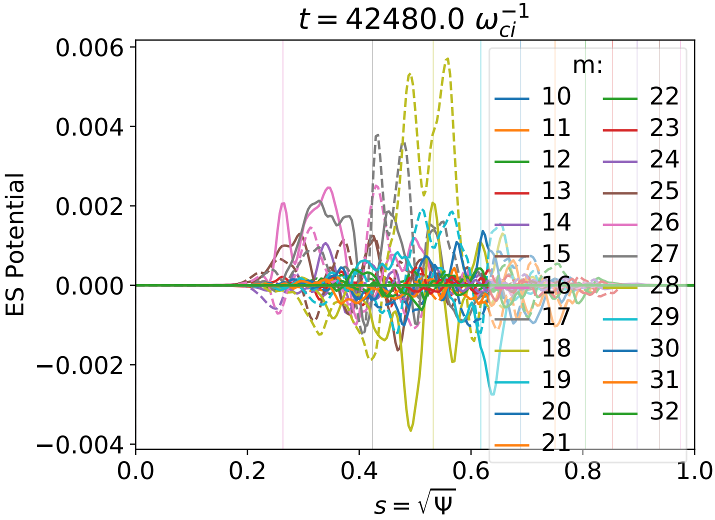
Nonlinear scan

Low beta ($\beta_\mathrm{e} = 0.0005$)



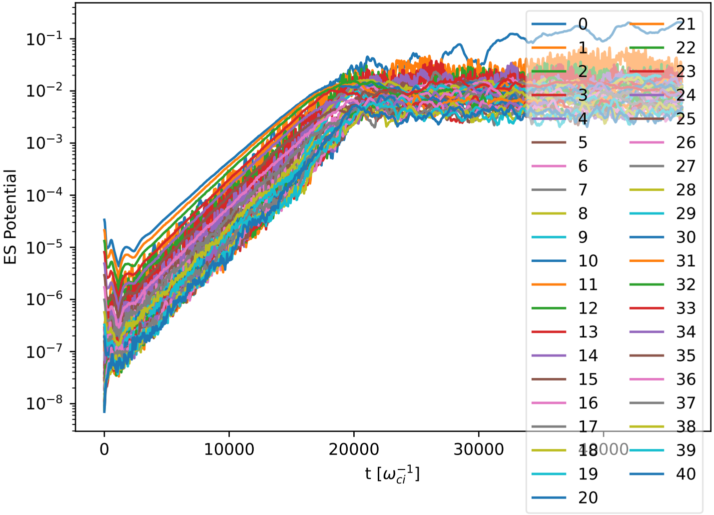
Nonlinear scan

Low beta ($\beta_e = 0.0005$)



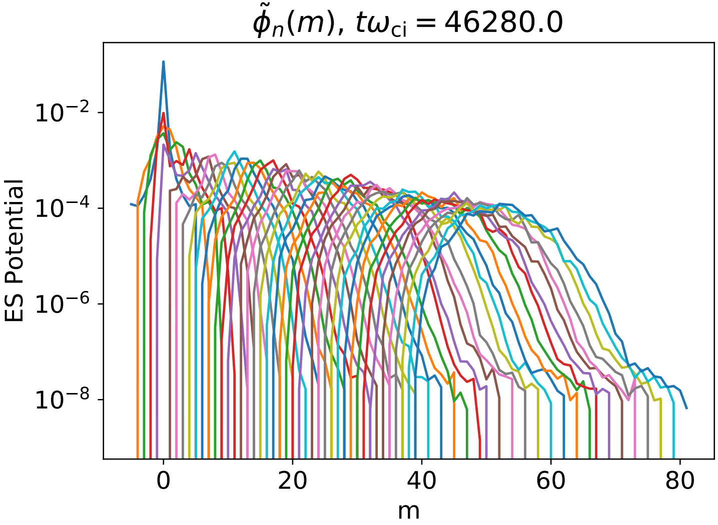
Nonlinear scan

High beta ($\beta_e = 0.0024$)



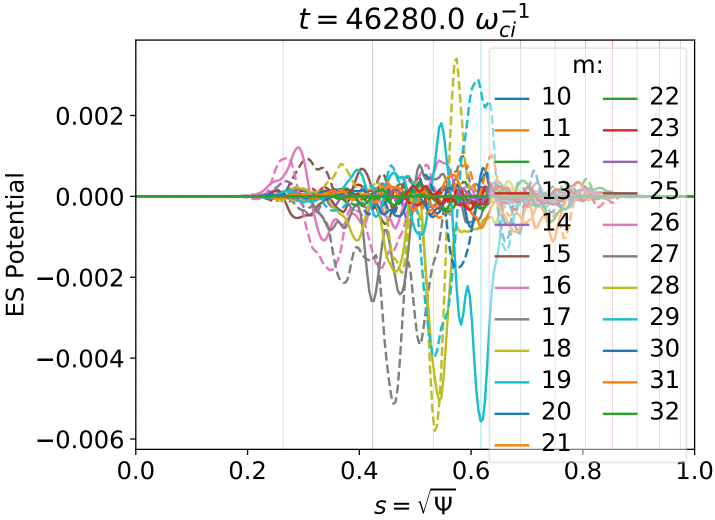
Nonlinear scan

High beta ($\beta_e = 0.0024$)



Nonlinear scan

High beta ($\beta_\mathrm{e} = 0.0024$)



Conclusions & Outlook

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- Electromagnetic AITG modes found in experimental cases (ITER, JET, AUG)
  - Especially at low/zero shear
  - Flute-structure
- In simplified geometry, simple 1D "ITG -> KBM" picture becomes 2D, less simple
  - Rational surfaces
  - Shift to low-*k*
- Addition of EPs complicates matters non-trivially (to be continued...)
- Nonlinear case retains certain flute rational surface effects

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- More detailed impact of EPs to be further investigated
- Effect of magnetic geometry (density of rationals)
- Choice of electromagnetic model
  - e.g. magnetic compression [Scott, McMillan, Mishchenko, Sheffield]
- Investigate the nature of phase-space