Max-Planck-Institut für Plasmaphysik

Global electromagnetic gyrokinetic simulations of energetic particle driven instabilities in ITER and ASDEX Upgrade

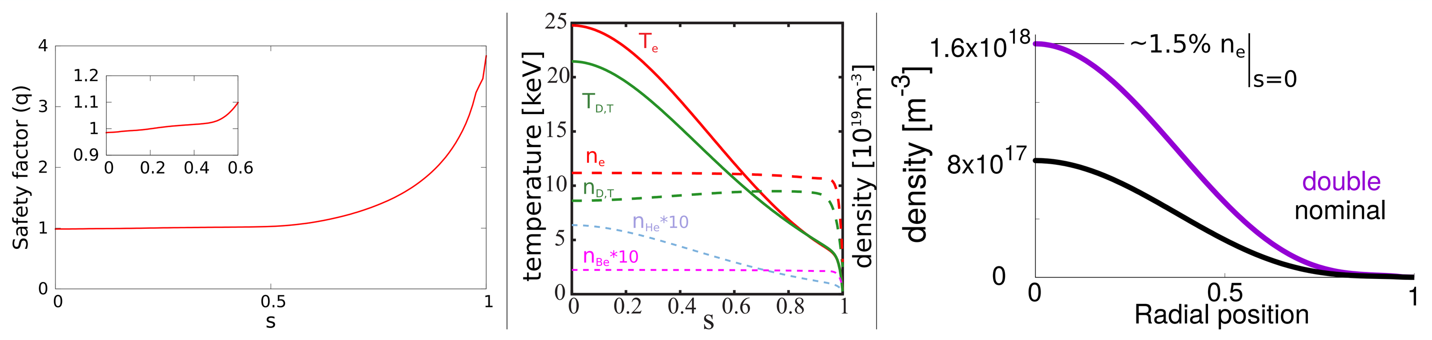
T. Hayward-Schneider[1]*, F. Vannini[1], Ph. Lauber[1], A. Bottino[1], Z.X. Lu[1], S. Günter[1]
email: thomas.hayward@ipp.mpg.de

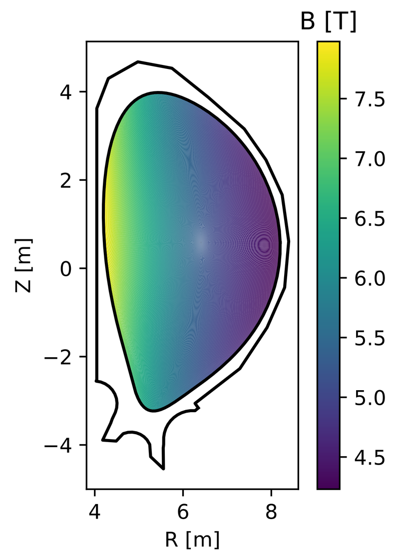
[1]Max Planck Institute for Plasma Physics, Garching, Germany

Motivation

ITER will present a challenge in terms of dealing with significant quantities of fusion alpha particles for the first time. While the ITER 15MA scenario [1] has received plenty of attention in the past [2-9], the models used to address the problem vary, and have not all agreed. In this work, we apply the global electromagnetic gyrokinetic model, using the ORB5 code [10], to the problem of nonlinear Toroidal Alfvén Eigenmodes (TAEs) in the ITER 15MA scenario, and to nonlinear Energetic Particle Mode (EPM)/Energetic particle driven Geodesic Acoustic Mode (EGAM) interaction in ASDEX Upgrade (AUG).

ITER 15MA Scenario

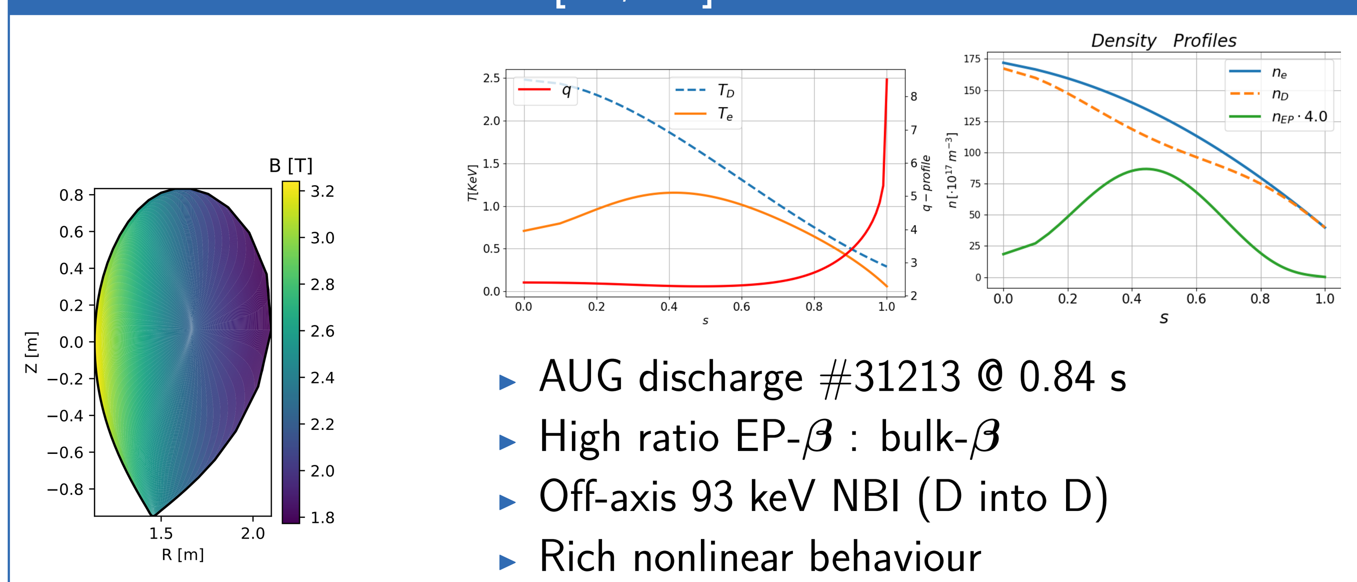




Compared to the nominal scenario (above), we make the following changes:

- Remove steep gradients at the plasma edge (around s>0.9)
- Neglect the trace impurities (He & Be)
- Treat the alpha particles as 900 keV Maxwellian species
- Replace 50:50 D:T mix with $^{2.5}$H isotope
- Consider double (and nominal) alpha density

"NLED-AUG" Scenario [16, 17]



- AUG discharge #31213 @ 0.84 s
- High ratio EP-β : bulk-β
- Off-axis 93 keV NBI (D into D)
- Rich nonlinear behaviour
- In this work: treat EPs as bump-on-tail: $v_{\parallel,\mathrm{bump}} = \pm 8\sqrt{T_e/m_i}$

Numerical tool: ORB5

"ORB5: a global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry" [10]

- Originally developed at SPC (Switzerland)
  - now at SPC, IPP (Germany) and Univ. of Warwick (UK)
- 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 [11] (leads to an order of magn. increase of time step)
- Drift-kinetic, fluid, hybrid, and adiabatic electron models present:
  - These results all with kinetic electrons (ITER: $m_e/m_i = 1/200$; AUG: realistic $(1/3676)$)
- Gyrokinetic (GK) or drift-kinetic (DK) ions (here: ITER: bulk GK, EPs DK, AUG: GK)
- Previously used for turbulence studies as well as EP physics:
  - ITPA-TAE benchmark [12], DIII-D RSAE/TAE benchmark [13]

Numerical parameters:
all ITER presented simulations were performed using $\{32, 128, 32\} \cdot 10^6$ markers for the bulk ions, electrons, and EPs respectively.
Full radius simulations used a grid of $(1024, 512, 128)$ in the radial, poloidal, and toroidal directions, $(512, 256, 128)$ for reduced annulus $(0.2 - 0.7)$.
For large n (> 30), the poloidal and toroidal grids were increased, for some cases with small n, reduced.
Unless otherwise stated, the timestep was $1.875\ \omega_{ci}^{-1}$. $\omega_{ci}/\omega_A \sim 187$, $\omega_A \sim 1.05 \times 10^6$ rad s^{-1}.

For AUG simulations, $\{30, 120, 30\} \cdot 10^6$ markers were used, and the grid was $(288, 288, 48)$ (full radius). The timestep was $3\ \omega_{ci}^{-1}$. $\omega_{ci}/\omega_A \sim 20.7$.

Conclusions

- Global, electromagnetic gyrokinetic code ORB5 applied to TAEs in ITER 15MA scenario and EPM/EGAM in ASDEX Upgrade scenario
- Systematic linear studies for both reduced annulus and full domain simulations
- Nonlinearly, saturation levels *enhanced* by multi-mode interaction

Results: ITER TAE modes

Examples of mode evolution: For low/medium mode numbers, such as $n = 12$, we see global structures, and the presence of multiple coexisting modes. For higher mode numbers, such as $n = 30$, modes are well localized.

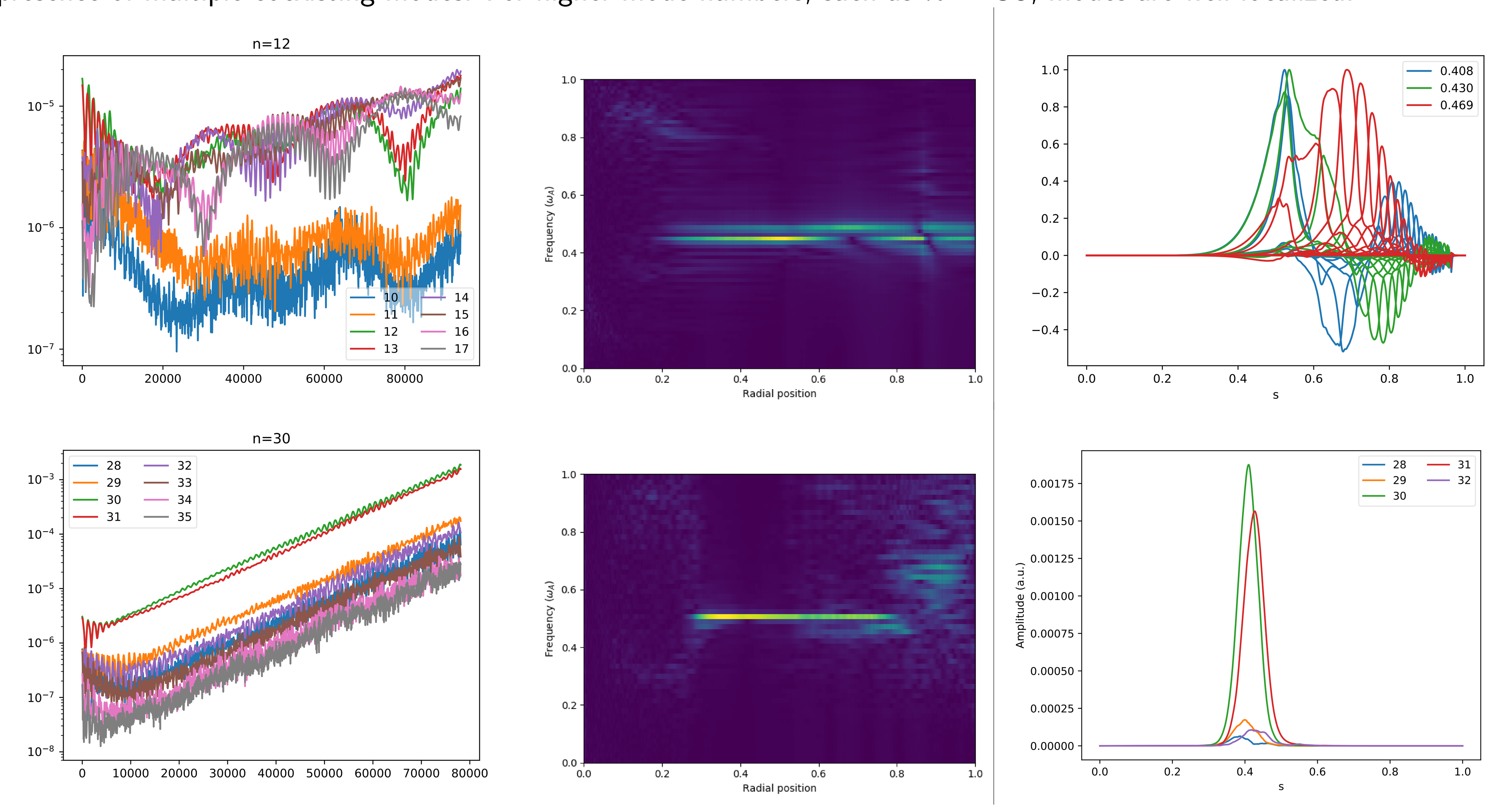
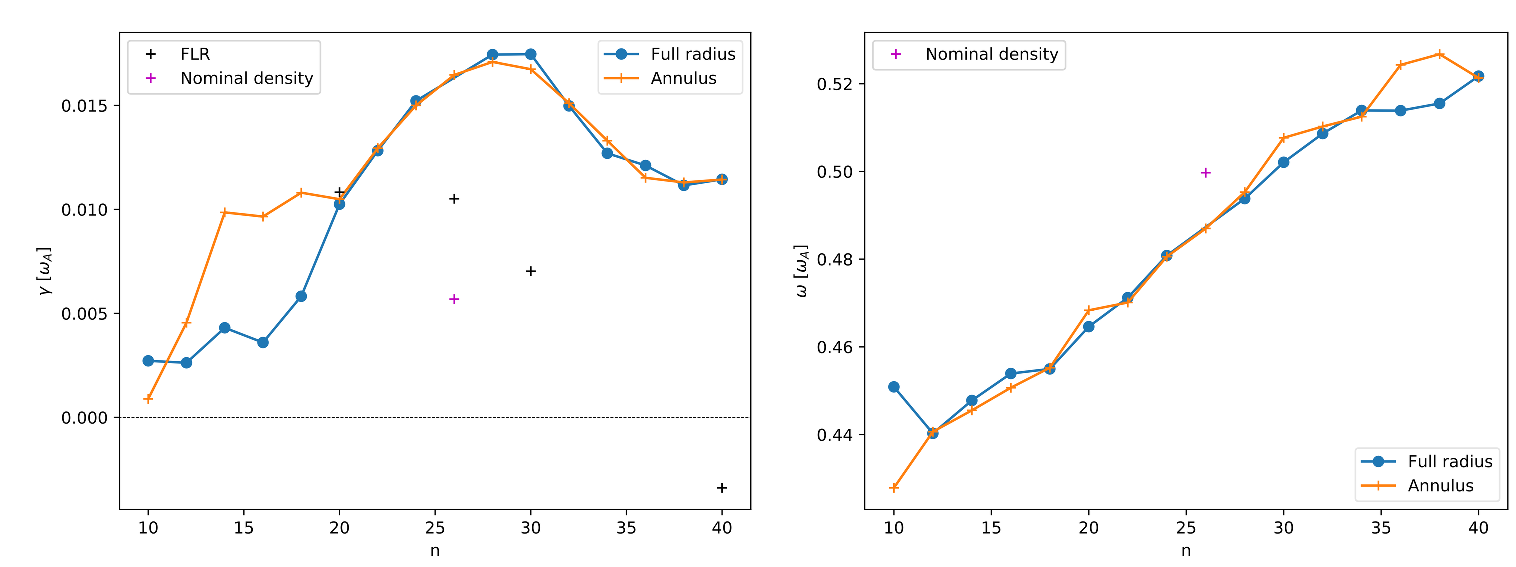


Fig. (Upper): $n = 12$: Evolution of the harmonics of the electrostatic potential (left), spectrogram (middle). We compare these to eigenfunctions obtained from LIGKA (right).
Fig. (Lower): $n = 30$: Evolution of the harmonics of the electrostatic potential (left), spectrogram (middle), obtained from ORB5. (Right): $n = 30$ eigenfunction from ORB5.

TAE linear spectrum:



Putting this together, we perform simulations with both full radius and annular $(0.2 \leq s \leq 0.7)$ toroidal mode numbers ranging from $n = 10$ to $n = 40$. We include on the figures also the case with $n = 26$ with the nominal EP density (magenta). FLR points are shown in black. With the isotropic slowing down, we observe an increase in growth rate for $n = 26$ from $\approx 0.016\omega_A$ to $0.021\omega_A$ (not shown).

NL evolution

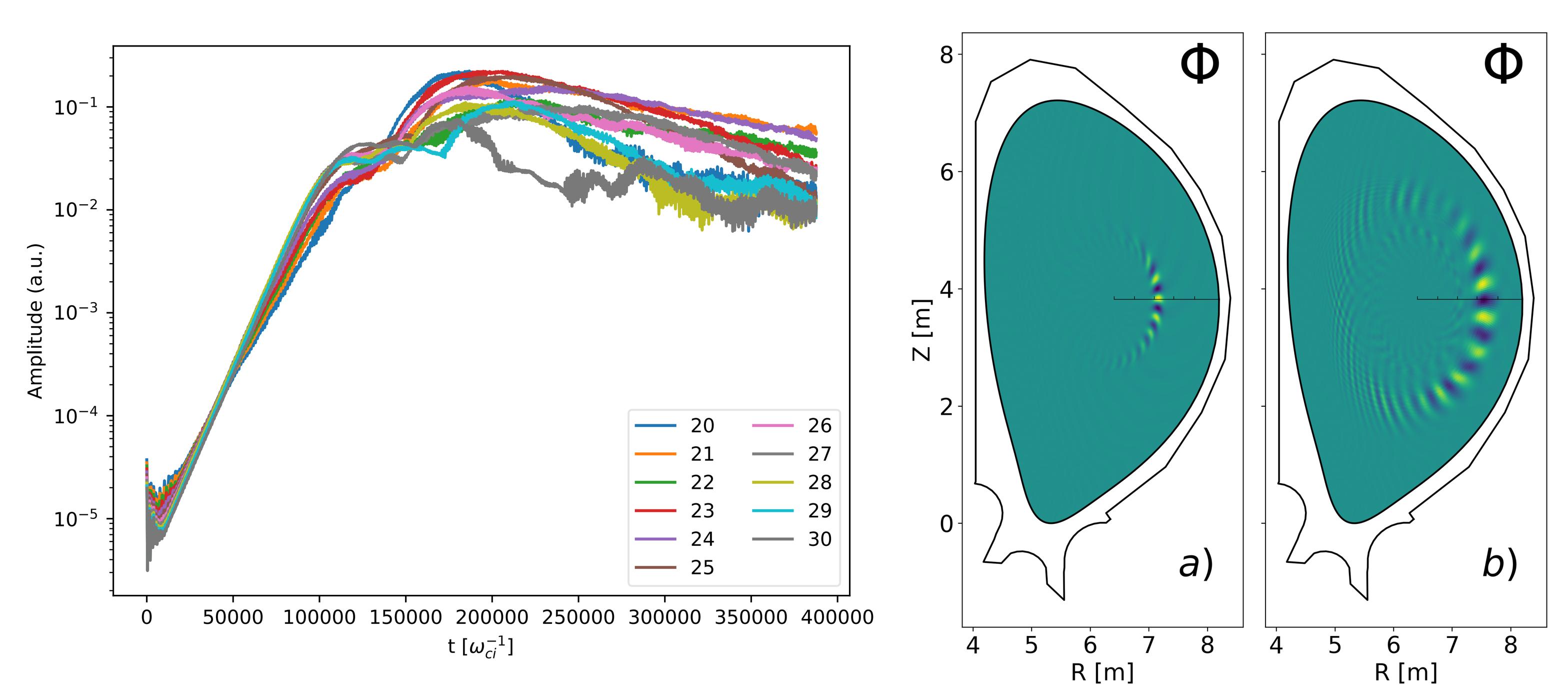


Fig.: (Left) Time evolution of the toroidal envelopes of the ES potential in a multi-mode $(20 \leq n \leq 30)$ annular simulation (10x markers). (Right) Snapshot of the electrostatic potential in the linear (a) and nonlinear (b) time of a global simulation, showing the spread to larger radius in the nonlinear phase [18].

Results: NLED-AUG

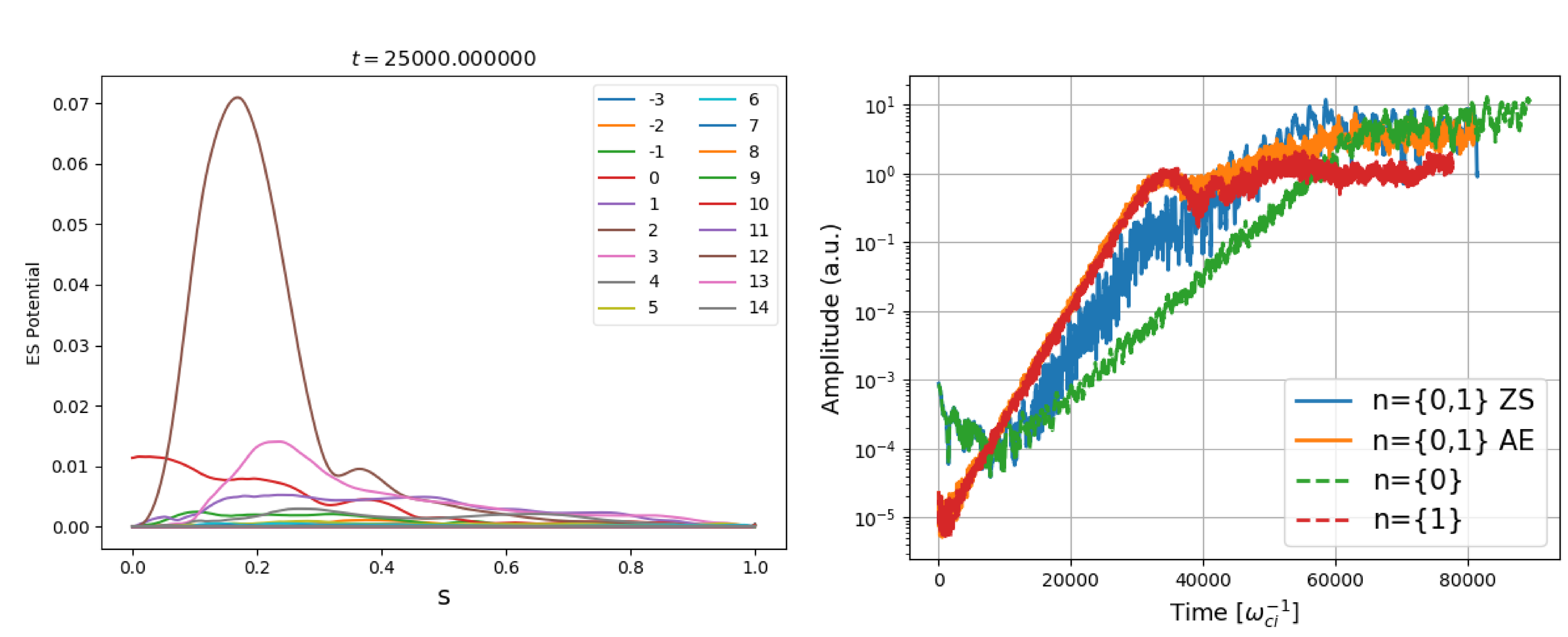


Fig: (left) $n = 1$, $m = 2$ EPM found (see [14] for related benchmark vs. MHD-Hybrid codes). (right) when considering $n = \{0, 1\}$ together, enhanced EPM saturation level observed vs. $n = 1$ EPM alone. This effect is found to depend on n_{EP} [15]

Simulations were performed under the projects ORBFAST and OrbZone on the EUROfusion Marconi supercomputer operated by CINECA and on the Cobra supercomputer of the Max Planck Society, operated by the MPCDF.

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