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Global electromagnetic gyrokinetic simulations of TAEs in ITER

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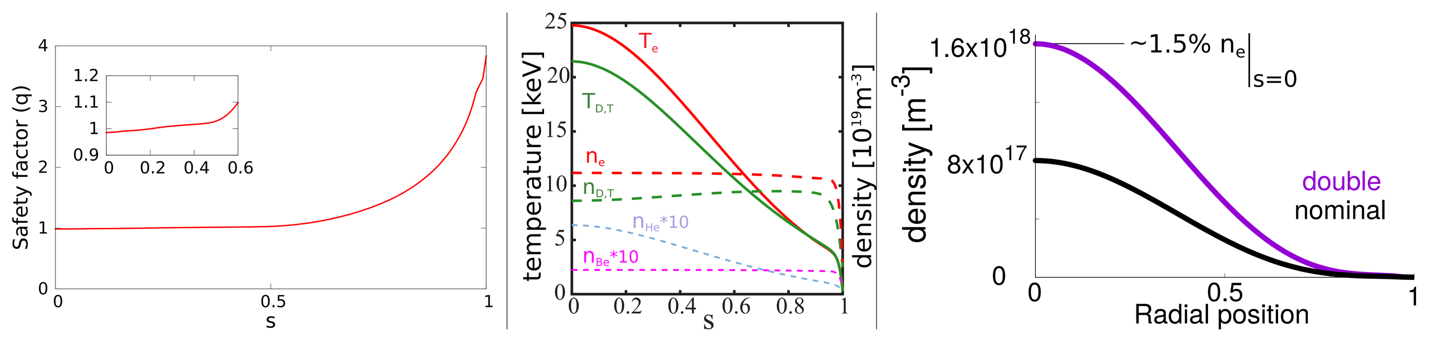
Motivation

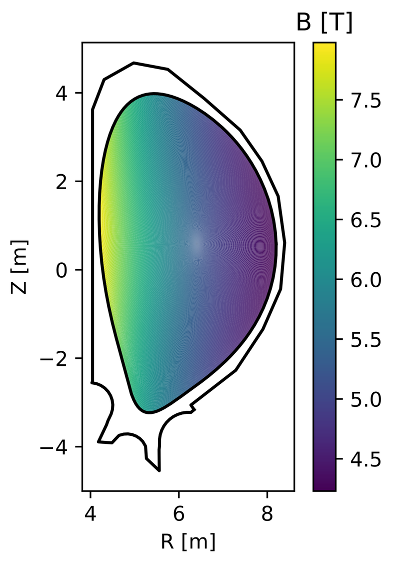
ITER will present a challenge in terms of dealing with significant quantities of fusion alpha particles for the first time. Their interaction with Alfvénic instabilities presents a challenge for modelling future scenarios.

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 present the application of an initial value global electromagnetic gyrokinetic model, using the ORB5 particle-in-cell code [10, 11], to the problem of Toroidal Alfvén Eigenmodes (TAEs) in the ITER 15MA scenario.

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

Numerical tool: ORB5

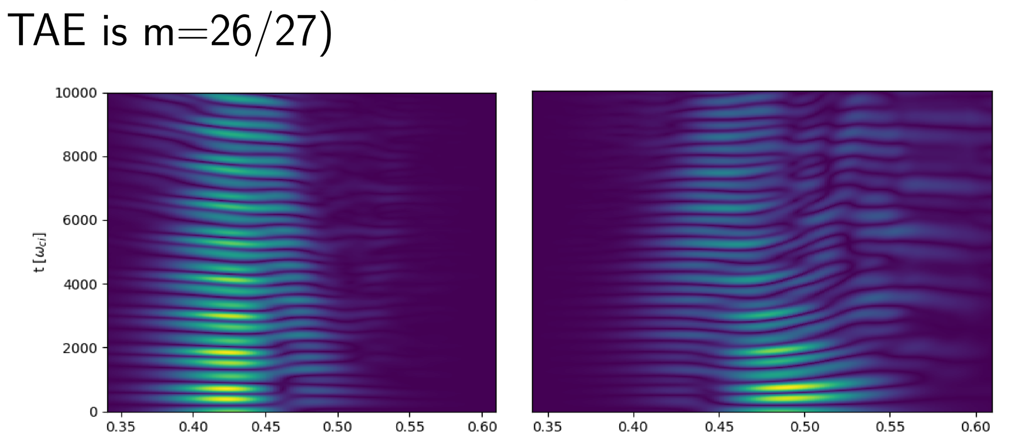
"ORB5: a global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry" [11]

- 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 [12] (leads to an order of magn. increase of time step)
- Drift-kinetic, fluid, hybrid, and adiabatic electron models present:
  - These results all with kinetic (reduced mass ratio) electrons
- Gyrokinetic or drift-kinetic ions (here: bulk gyro-, EPs drift- kinetic)
- Previously used for turbulence studies as well as EP physics:
  - ITPA-TAE benchmark [13], DIII-D RSAE/TAE benchmark [14]

Numerical parameters:
all 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}.
Annular simulations have a cost of $\sim$ 0.5 core-hr per step, full radius $\sim$ 0.9.

Results: Radiative damping

If we look at the the subdominant harmonics either side of the mode, shortly after initialization, we see radially propagating waves, indicative of KAW (here m=25/28, TAE is m=26/27)



Conclusions

- Global, electromagnetic gyrokinetic code ORB5 applied to TAEs in ITER 15MA scenario
  - Robust scenario, only minor modifications to profiles made
- Systematic linear studies for both reduced annulus and full domain simulations
- Nonlinear, multimode studies begun

[1] A. Polevoi *et al.* JFR (2002)
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[10] S. Jolliet *et al.* CPC (2007)
[11] E. Lanti *et al.* CPC (sub.)
[12] A. Mishchenko *et al.* CPC (2019)
[13] R. Hatzky *et al.* NF (2018)
[14] S. Taimourzadeh *et al.* NF (2019)

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

Results: TAE modes

Example mode structures: Here we show two global simulation domain examples, run on the full radius $(0 \leq s \leq 1)$.

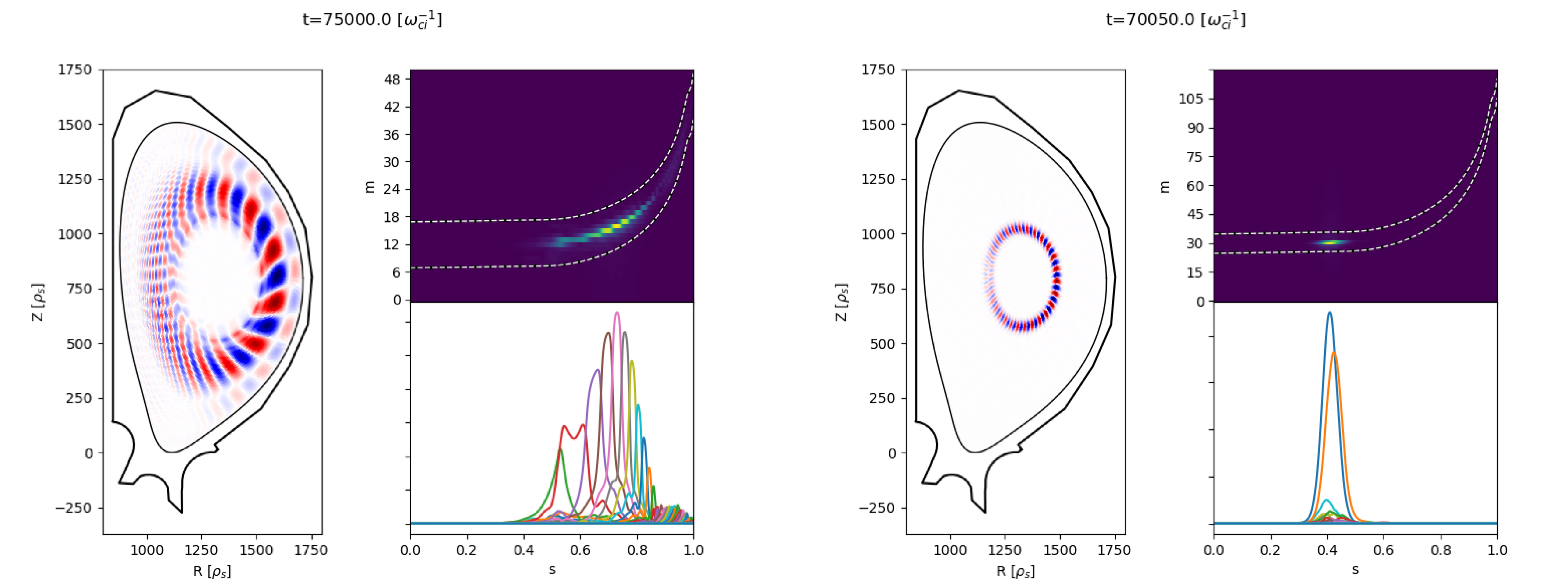


Fig. 1: Snapshots of the electrostatic potential for TAEs with $n = 12$ (left) and $n = 30$ (right). R / Z are in units of ρ_s.

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 $n = 30$, we see localized structures.

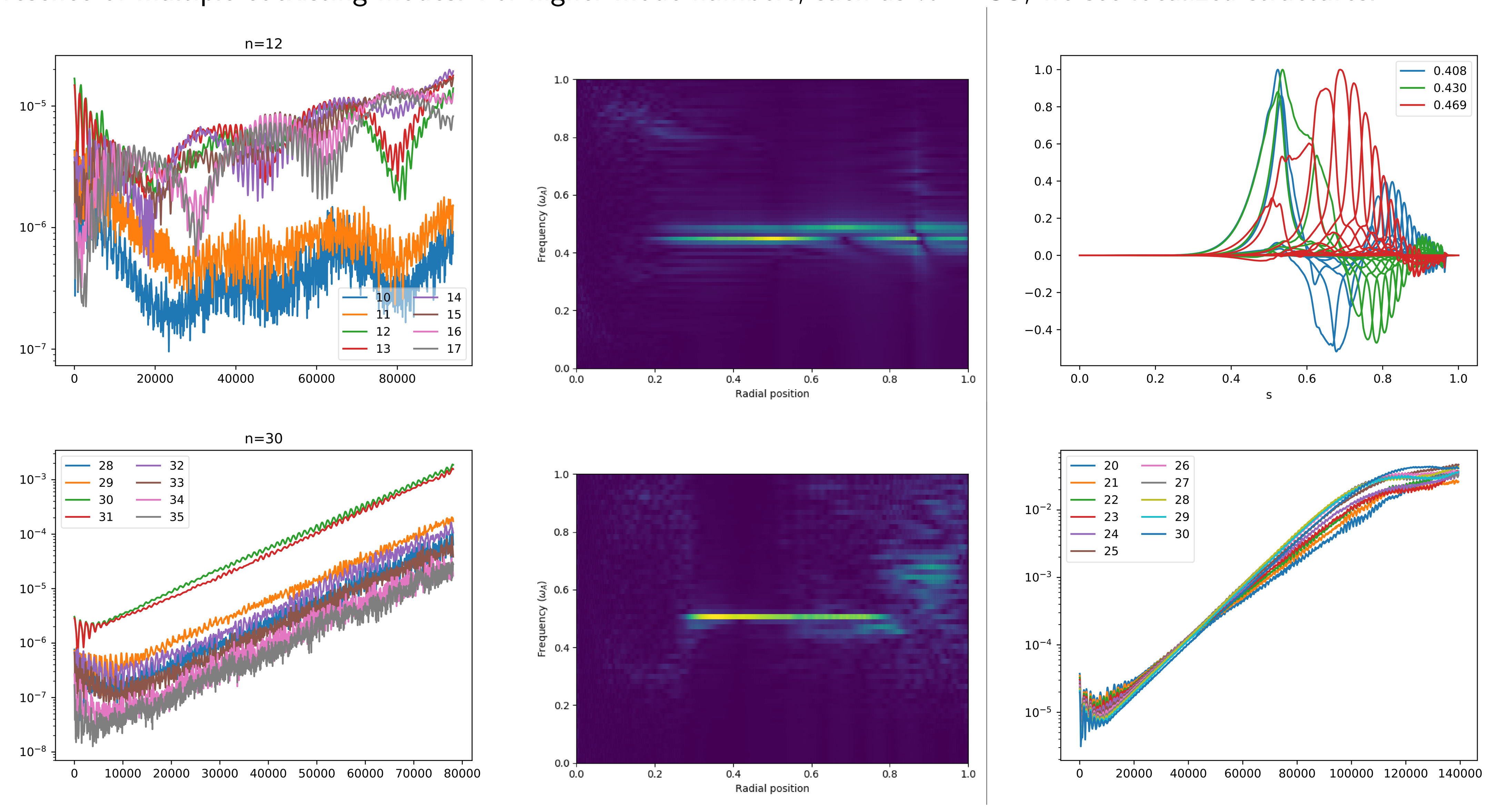


Fig. 2 (Upper): $n = 12$: Evolution of the harmonics of the electrostatic potential (left), spectrogram (middle). We compare these to eigenfunctions obtained from LIGKA (right).
Fig. 3 (Lower): $n = 30$: Evolution of the harmonics of the electrostatic potential (left), spectrogram (middle), obtained from ORB5. (Right), we show a multi-mode nonlinear simulation with $20 \leq n \leq 30$ allowed in the filter. This simulation was run with 10x the number of markers, and on an annular domain (note that the legend here refers to n).

Effect of the electron mass: We expect a dependence of the electron mass on the electron Landau damping. Also a numerical dependence on the permitted timestep as the electrons become lighter (faster).

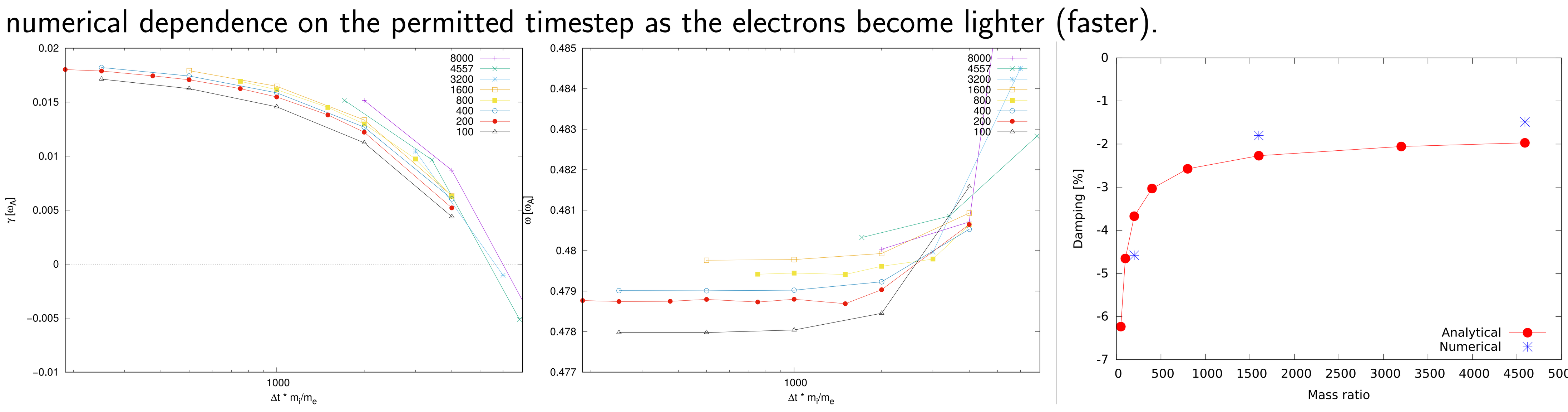
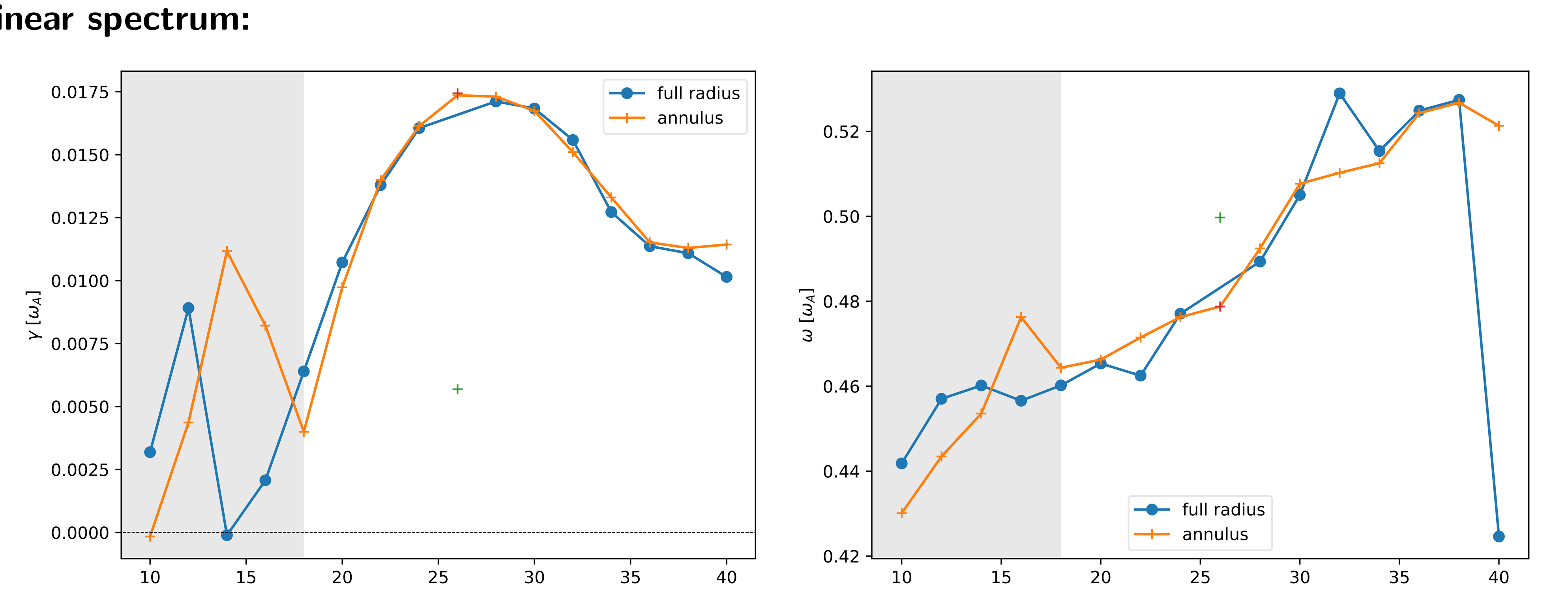


Fig. 4: Convergence with the time step of the growth rate (left) and frequency (middle) of the $n = 26$ TAE (annular domain, $0.2 \leq s \leq= 0.7$) for different m_i/m_e (legends). We see a systematic offset towards an increase in damping for the cases with heavy electrons. (Right) the damping rates from LIGKA (background plasma only) for heavy electrons.

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 $n = 40$. The case of $n = 26$, annular is as included above in the electron mass/dt study. For that case, we include on the figures also the case with $n = 26$ with the nominal EP density. For lower n (< 18), we see multiple unstable modes, or the most unstable mode is not the one most strongly initialized, therefore the error on a simple fit for the growth rate is considerable (grey background).

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