Nonlinear dynamics of frequency chirping EPM by HMGC & Orb5 simulations of frequency chirping modes: towards turbulence + EP

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Orb5 simulations: X. Wang, A. Mishchenko, T. Hayward-Schneider, A. Boltino, Ph. Lauber, Z. Lu and A. Biancalani

Introductions and motivations

- Highlighted analysis on EPM chirping by HMGC
- Preliminary results of EPM like frequency chirping modes simulated by using fully gyrokinetic code Orb5.
- Detail analysis technique. (e.x. HMGC hamiltonian mapping etc.)
- Turbulence effects on EP driven modes.

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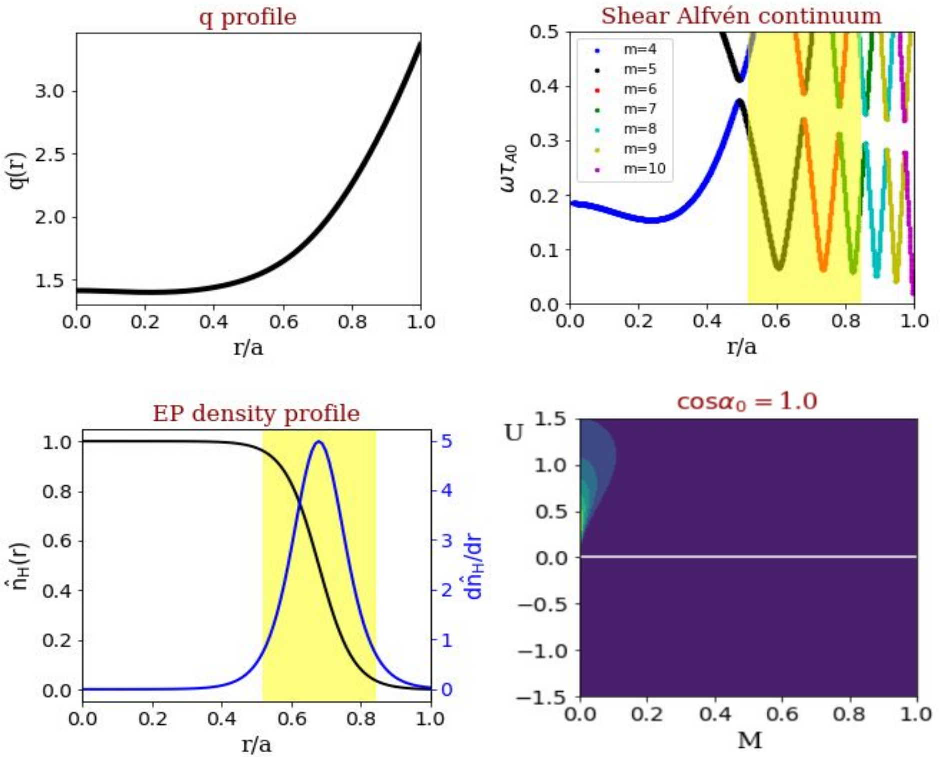
HMGC Simulation settings



1. TAE gaps are within the region.
2. Relevant large shear
3. The drive is relatively narrow.
4. Single - n=3
5. In HMGC, shifted circular magnetic surface is assumed, and inverse aspect ratio is 0.1.

Energetic particle distribution function:

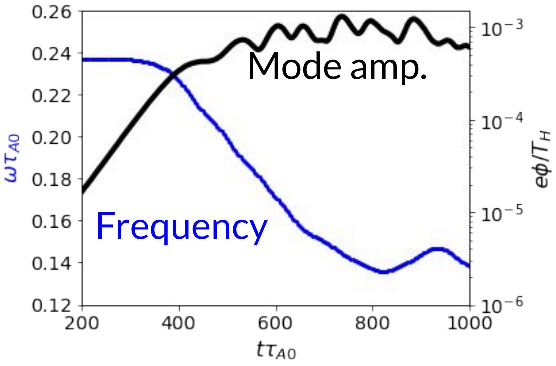
$$f_{sd} = \frac{n_{H0}\,\hat{n}(\psi)}{E_{crit,0}^{3/2}\,\tau(\psi)^{3/2}}\,\frac{3}{4\pi}\left(\frac{m_H}{2}\right)^{3/2}\frac{\Theta(\alpha,\alpha_0,\Delta)}{\left[\left(E/E_{crit}\right)^{3/2}+1\right]\ln\left[1+\left(E_0/E_{crit}\right)^{3/2}\right]}$$

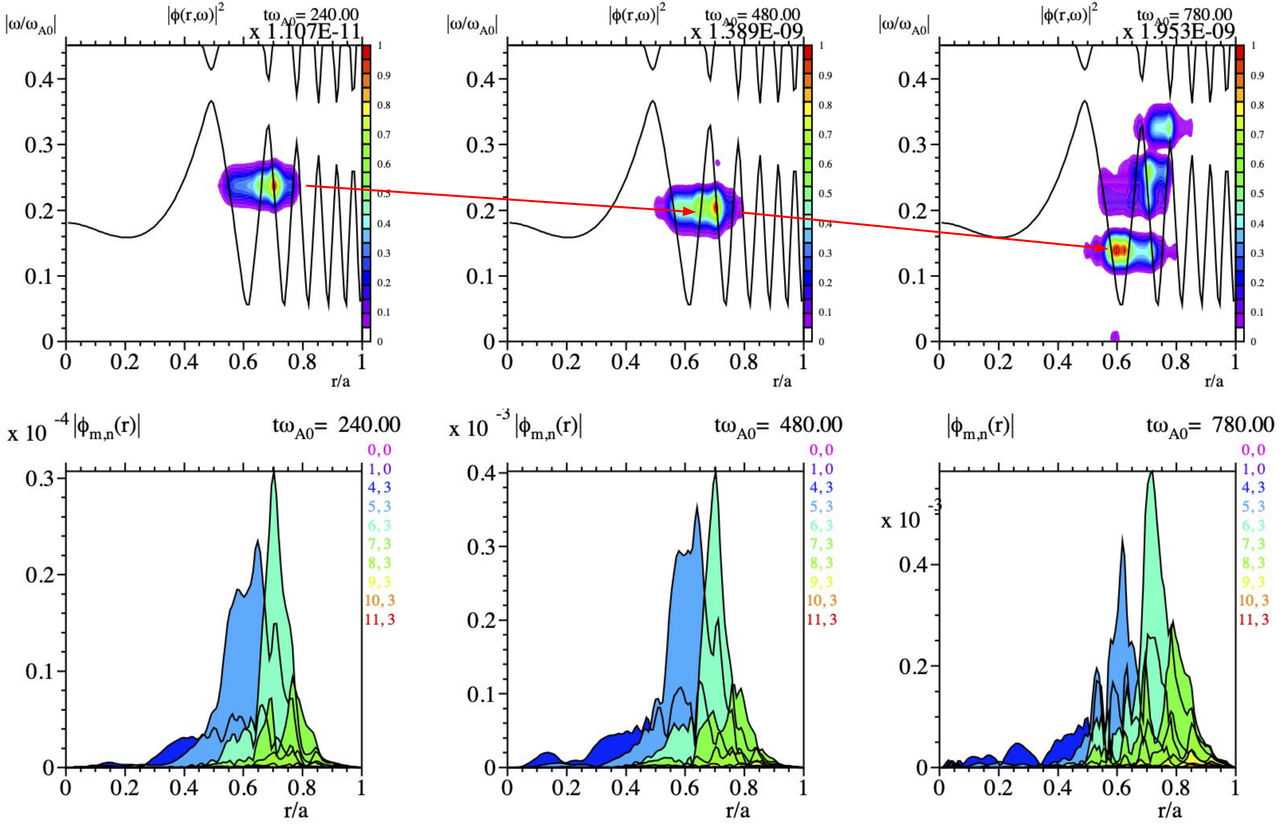
$$\cos\alpha \equiv \frac{u}{\sqrt{2E/m_H}} \qquad \Theta(\alpha,\alpha_0,\Delta) = \frac{4}{\Delta\sqrt{\pi}}\,\frac{exp\left[-\left(\frac{\cos\alpha-\cos\alpha_0}{\Delta}\right)^2\right]}{erf\left(\frac{1-\cos\alpha_0}{\Delta}\right)+erf\left(\frac{1+\cos\alpha_0}{\Delta}\right)}$$

The features of non-perturbative EPM

- EPM is driven unstable can be understood from the general fishbone-like dispersion relation (Chen&Zonca RMP2016 and references therein)

$$i\Lambda = \delta W_f + \delta W_k$$





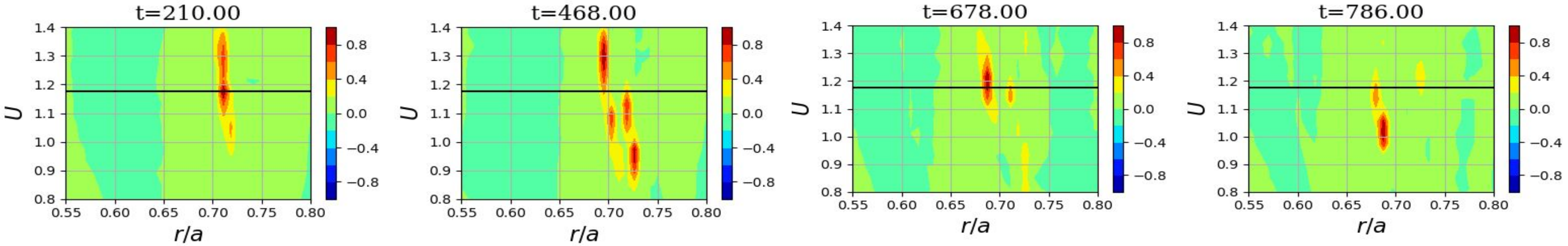
Power exchange in initial coordinate space

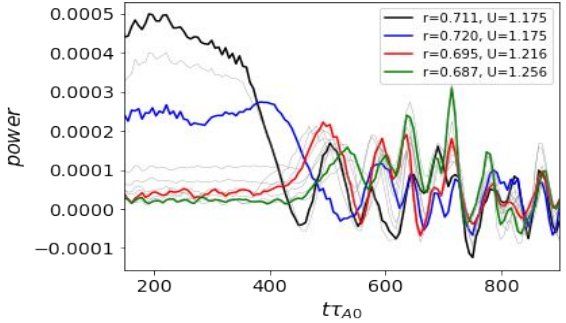
Questions:

- For the relevant linear resonant particles: what's the power exchange during the nonlinear phase?

Method:

- The coordinate transformation from Z to Z_0 is complicated in an analytical frame, however it is trivial numerically by storing particle initial coordinates.





- Time evolution of the power transfer (averaged over θ and Φ) at the most relevant grid points in the discretized space (r_{eq0}, U_{eq0}, M=0).
- The particles dominating the drive during the linear stage, lose importance, being replaced at different time by different particles.

Test particle analysis

- For the identified 2D maxima of power exchange, we choose a test particle population characterized by the corresponding value of M and U_0 and different values of r.
- We collect information, for each particle, at each crossing of the equatorial plane (θ=0, the outer equatorial position).
- The wave-particle phase takes into account the frequency chirping.

$$\Theta = \int_0^t dt' \omega(t') + m\theta - n\phi$$

- So, at the j-th equatorial crossing, we have

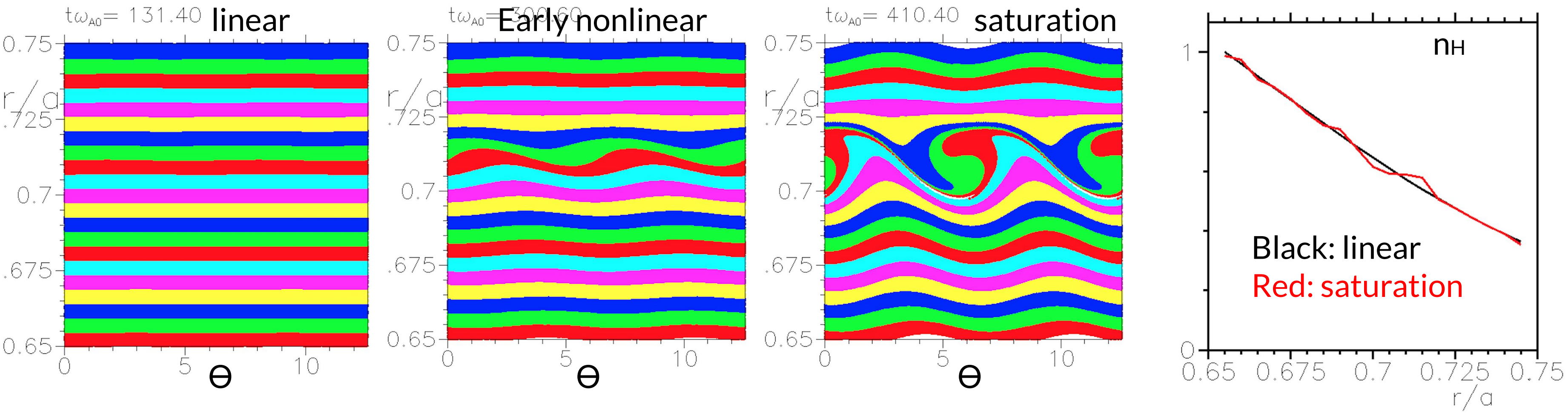
$$\Theta_j = \int_0^{t_j} dt' \omega(t') + 2\pi j m\sigma - n\phi_j ,$$

  with $\sigma = sign(U)$.
- The resonance condition becomes (k is the 'bounce harmonic')

$$\Delta\Theta_j \equiv \Theta_{j+1} - \Theta_j = \int_{t_j}^{t_{j+1}} dt' \omega(t') + 2\pi m\sigma - n\Delta\phi_j = 2\pi k$$

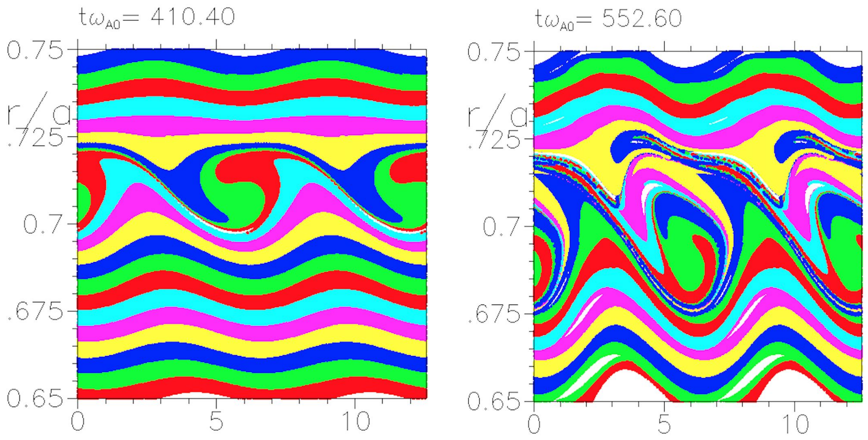
- It can be written as $\int_{t_j}^{t_{j+1}} dt' \omega(t') = n\Delta\phi_j + 2\pi(k - m\sigma)$

Test particle analysis

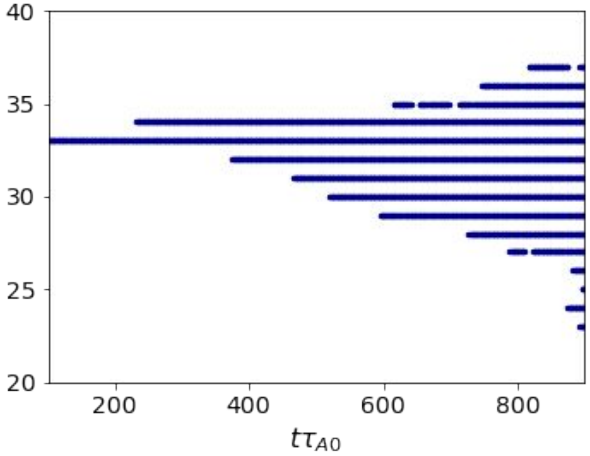


- Test particles (marker) (fig: left) colour is chosen according to the birth r_{eq} value of the particle.
- As the mode amplitude grows, (fig: middel) r_{eq} varies because of the mode-particle interaction (ExB drift).
- At (fig:right) saturation, an island-like structure forms.
- Particles outside the resonance region undergo a secular drift in phase.
- The formation of the island mixes particles born on both sides of the resonance radius, causing a density flattening.
- The flattening process causes mode saturation.
- What happens during frequency chirping?

Continuously trapping and detrapping: trapping

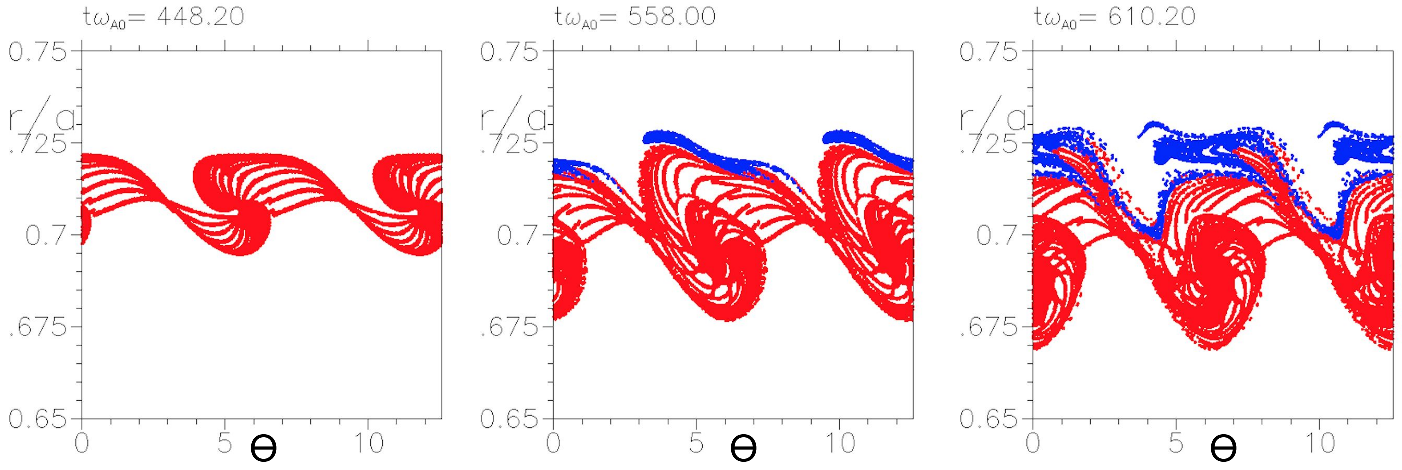


- The overall inward drift structure is evident.
- Newly 'trapped' particles are also observed.



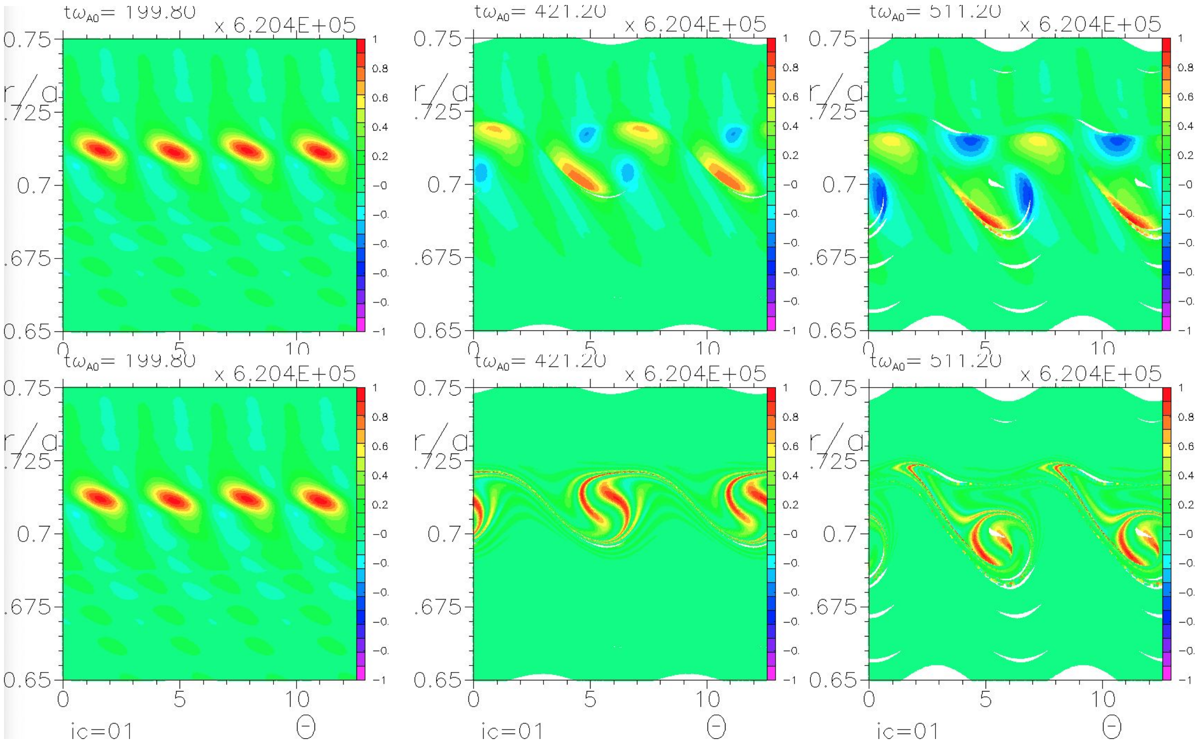
- At each time, the indices of the radial bands of test particles owning at least one particle able to satisfy fairly well the resonance condition (last phase variation less than 0.015). Both outward and inward (but more inward) trapping of new bands are observed.

Continuously trapping and detrapping: detrapping



- Consider a group of particles that satisfied the resonance condition.
- Colour is red for particles that appear still trapped in the wave.
- It switches to blue as the particle cumulates a phase drift greater than a certain conventional threshold. (2.5 π, in this case).
- During the structure moves inward, more and more particles are detrapped.

Test particle analysis: Power transfer rate



Each marker is coloured according to its own power-transfer rate.

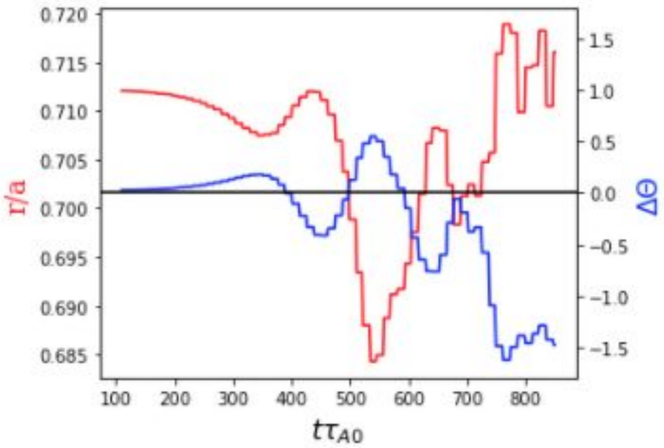
Question: the most destabilizing particles are the same or not?

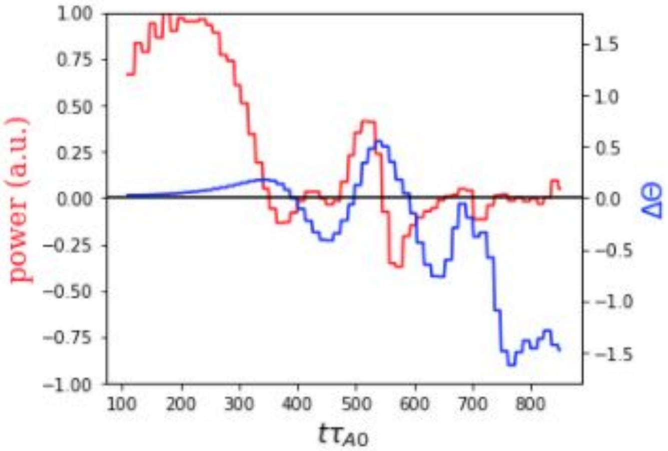
Each markers keep their color as in the very left plots.

Conclusion: the mode is driven, at different times, by not the same particles.

Test particle analysis: Power transfer rate

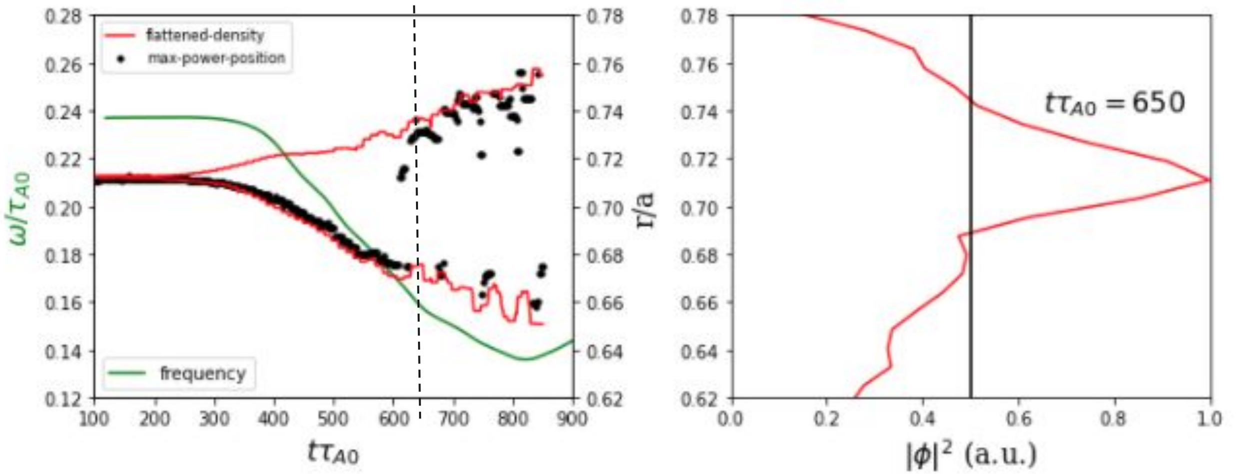
Question: at which condition, the power-transfer is the most efficient?





- The radial position, power transfer and $\Delta\Theta_j - 2\pi k$ (here k=-1) for one of the particles belonging to the linear max power-exchange group.
- Maximum power transfer and radial excursion occur when the particle is in the phase with the mode.
- Phase-locked particles can maximize power-exchange. (Zonca et al 2015)

Density flattening vs radial mode structure



- The flattened-density region is consistent with the large-gradient positions and continuously trapping boundaries.
- The maximum power transfer radial evolution follows the inward large density gradient radial positions.
- The efficient power transfer reduced due to radial decoupling.
- The frequency chirping rate also slows down when efficient power transfer reduces.

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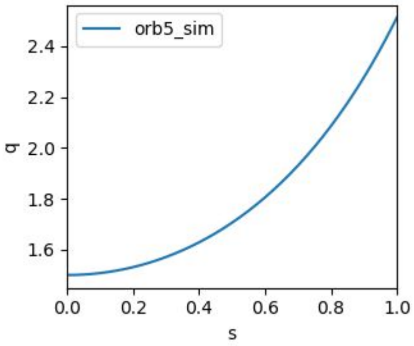
Simulation settings:

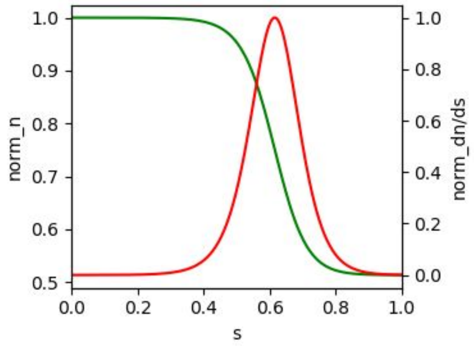
q profile

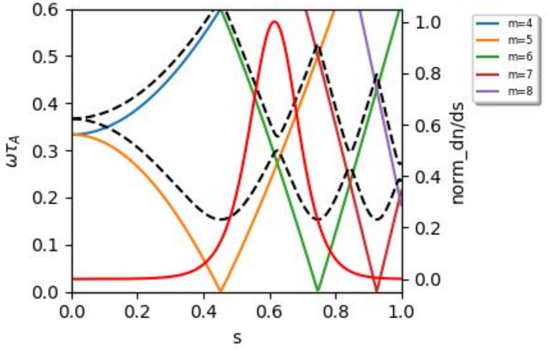
EP density profile

Shear Alfvén continuum

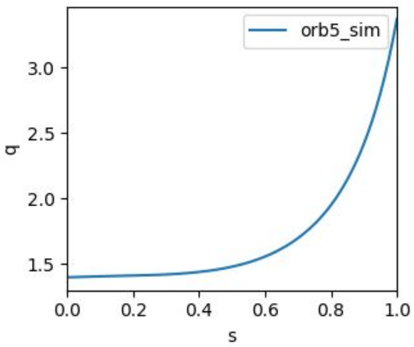
case1

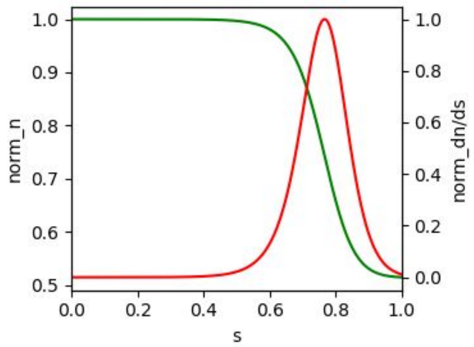


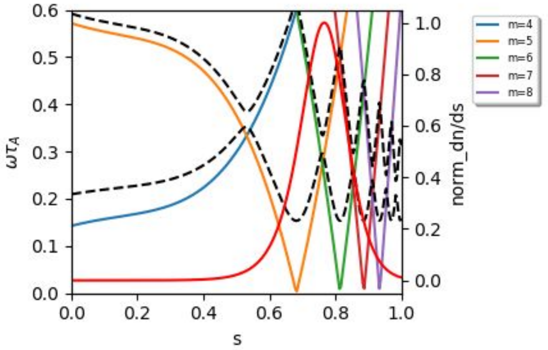




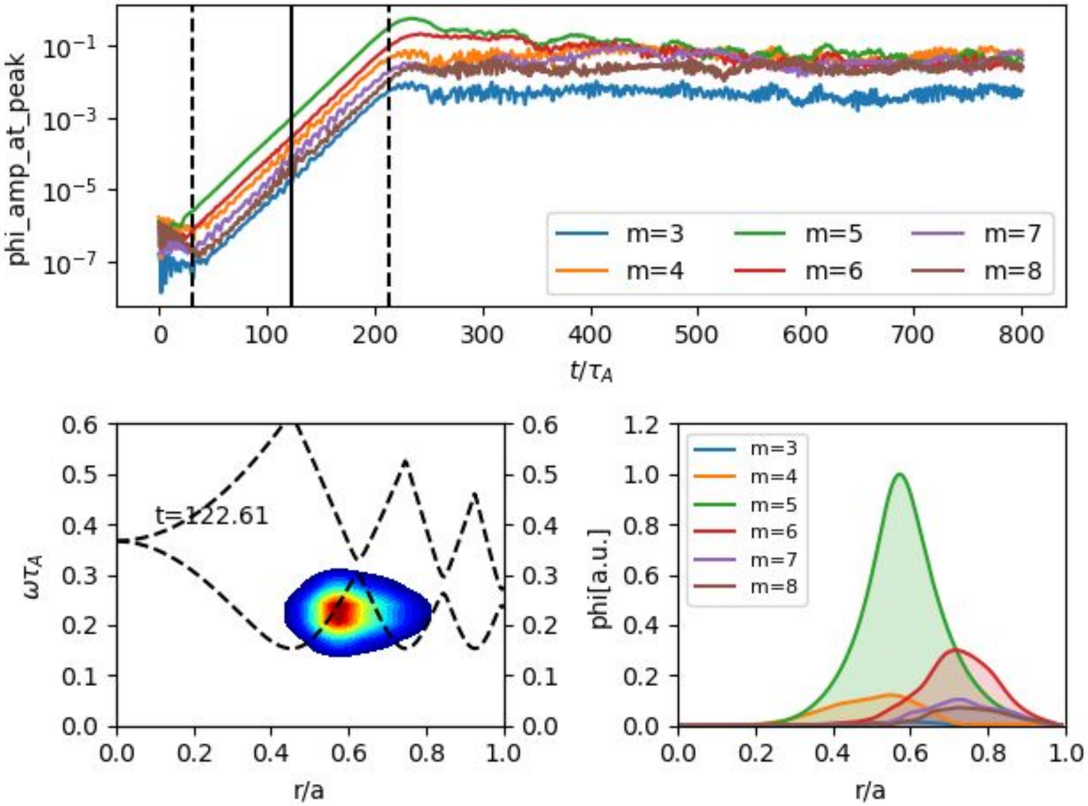
case2







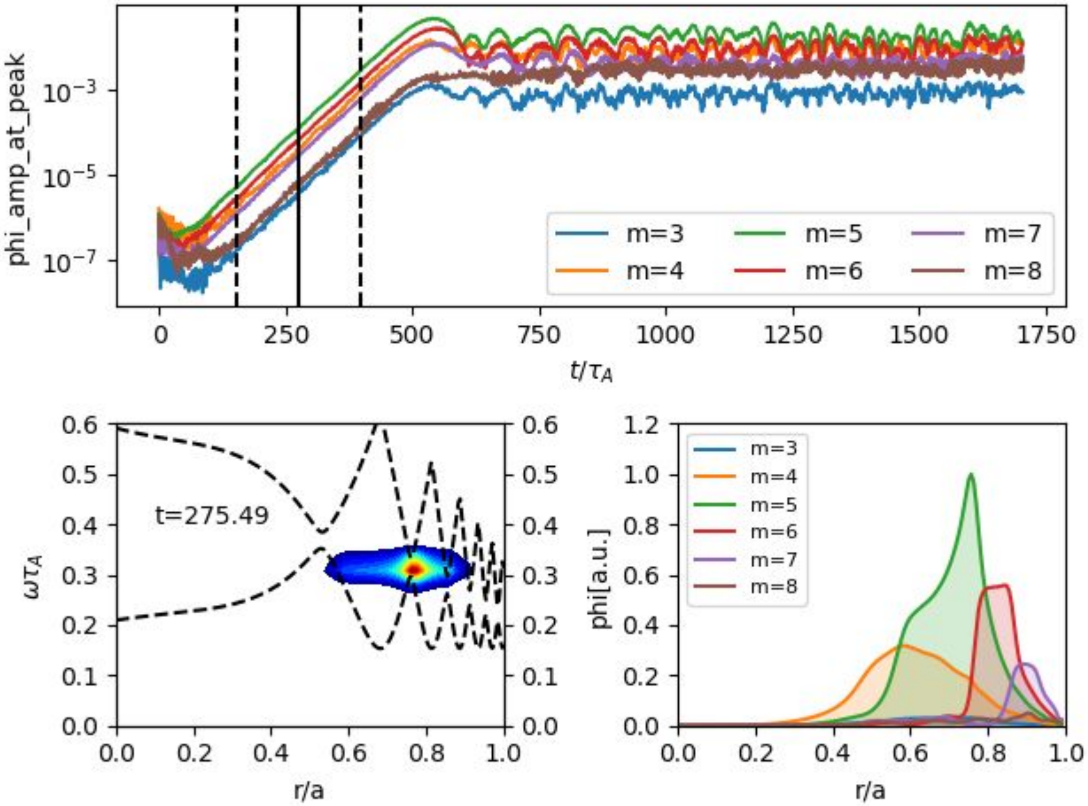
Case 1: with uniform (flat) bulk temperature and density



$\omega_L = 0.24$

$\gamma_L = 0.064$

Case 2: with uniform (flat) bulk temperature and density



$$\omega_L = 0.308$$

$$\gamma_L = 0.0247$$

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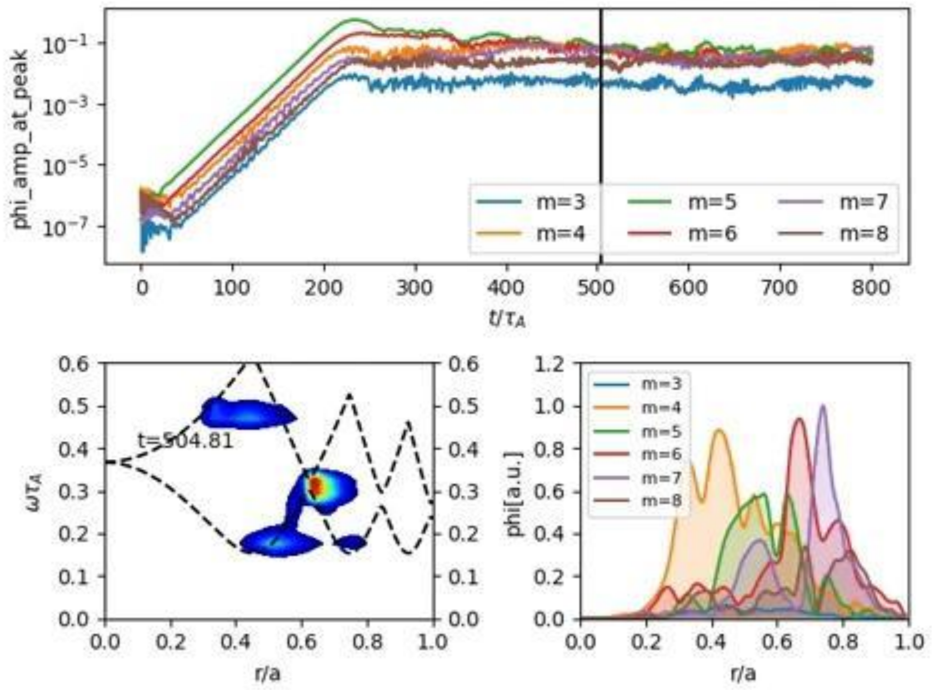

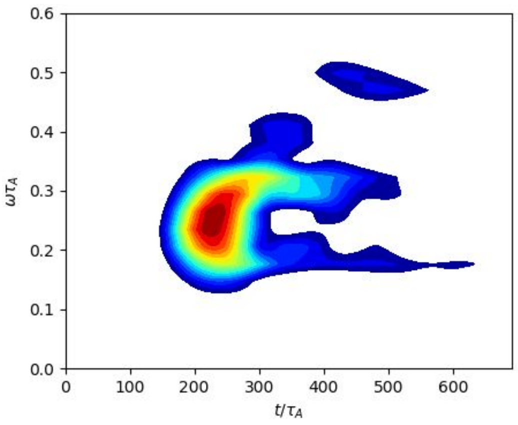

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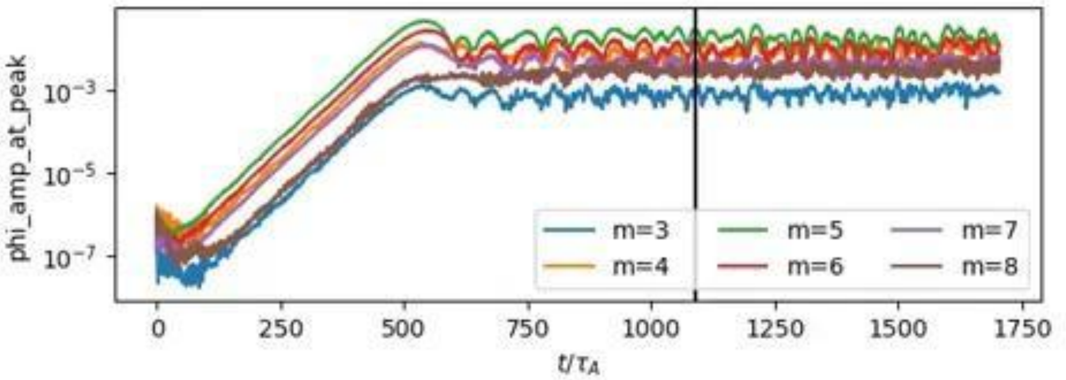
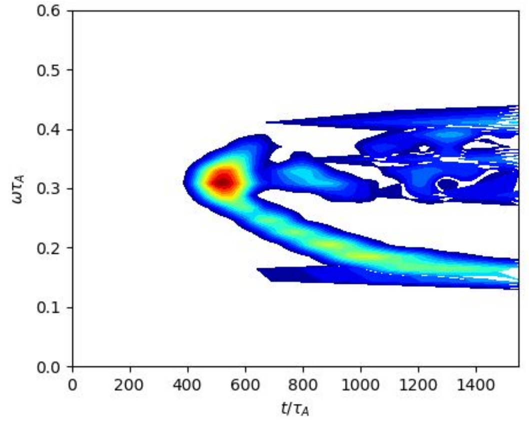
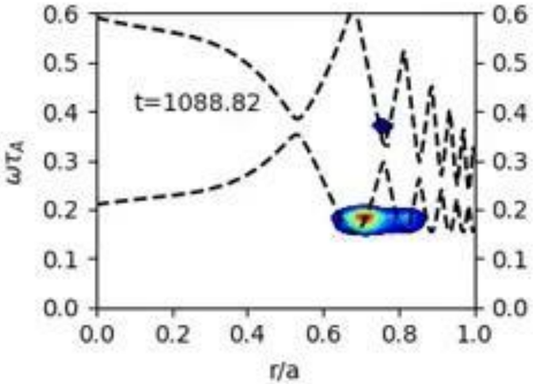
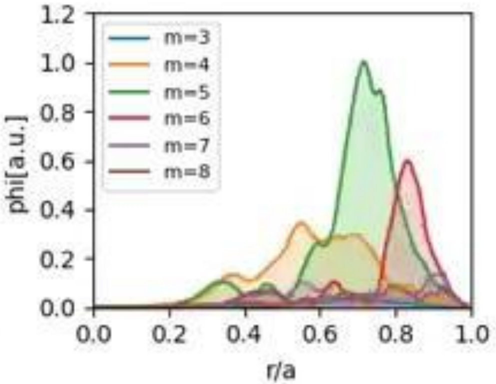
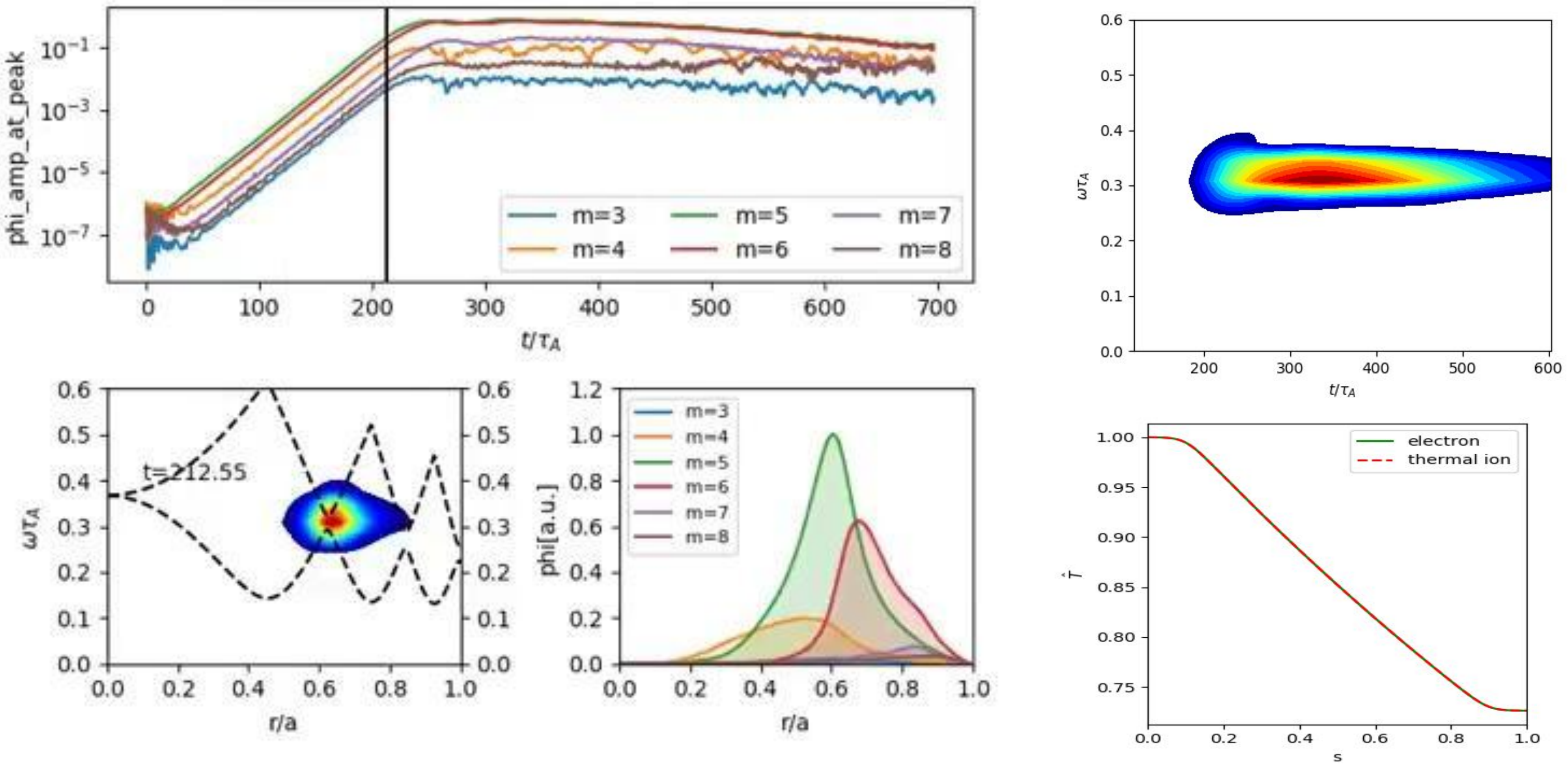








Case 1: with bulk plasma temperature gradient



Case 2: with bulk plasma temperature gradient