Nonlinear benchmark for TAEs: HMGC results

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HMGC

- Hybrid MHD-Gyrokinetic Code (HMGC):
  - thermal plasma described by $O(\varepsilon^3)$ reduced-MHD equations
  - energetic particles (EP) described by nonlinear guiding-center Vlasov equation (Particle-in-cell technique)
  - self-consistent simulations (particles treated non perturbatively: they contribute to MHD eqs. through pressure)
  - mode-mode coupling neglected in single-*n* simulations (but particle nonlinearities fully retained)

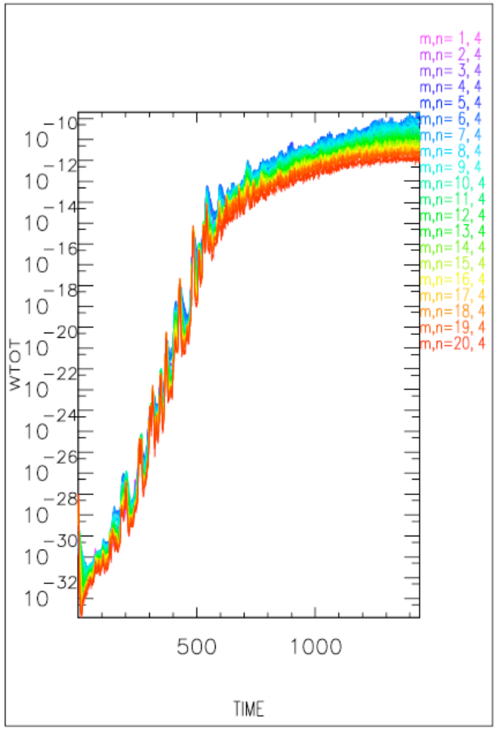
Nonlinear benchmark case

- R_0=2.53m, a=0.88m, B_0=5.1T
- $\beta(r) = 0.01\ (1-\psi^{0.8})^{2.7}$
- q(0)=1.6, q(1)=5, q'(0)=0, q'(1)=9.8
- $q(r)=q(0)+\psi\ [q(1)-q(0)+(q'(1)-q(1)+q(0))(1-\psi_s)(\psi-1)/(\psi-\psi_s)]$
- $\psi_s=[q'(1)-q(1)+q(0)]\ /\ [q'(0)+q'(1)-2(q(1)-q(0))]$
- $n_D = 3.85\ 10^{13}\ (1.-0.75\ \psi^{0.74})^{1.13}\ cm^{-3}$
- $n_e = 4.\ 10^{13}\ (1.-0.75\ \psi^{0.74})^{1.13}\ cm^{-3}$
- $Z_{eff} = 2.44$
- $T_i = 11.26\ (1.-0.5\ \psi)^{5.5}$ keV
- $T_e = 6.\ (1.-0.5\ \psi)^{5.5}$ keV
- E_0=3.52 MeV, $v_\alpha = 1.3\ 10^9$ cm/sec
- $v_A = 1.27\ 10^9$ cm/sec
- $m_\alpha = 4\ m_p$
- $z_\alpha = 2\ z_p$
- $\beta_\alpha = 0.00083\ \exp[-(\psi^{1/2}/0.42\ )^{2.55}]$
- Slowing down distribution function for EP

HMGC simulations

- Note: EP distribution function is not a function of unperturbed motion invariants (ψ is not a constant of motion)
- Simulations do not describe the evolution around a true equilibrium

- The lowest order distribution function evolves with time scales shorter than that needed for the formation of the radial structure of the mode
- The growth observed is due to the succession of transient wave packet growths
- No mode growth rate can be defined for low drive cases

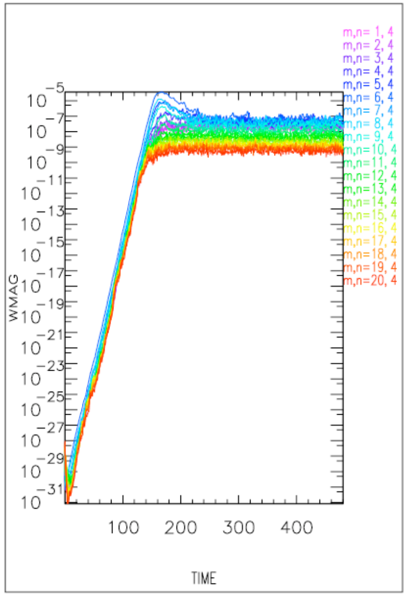


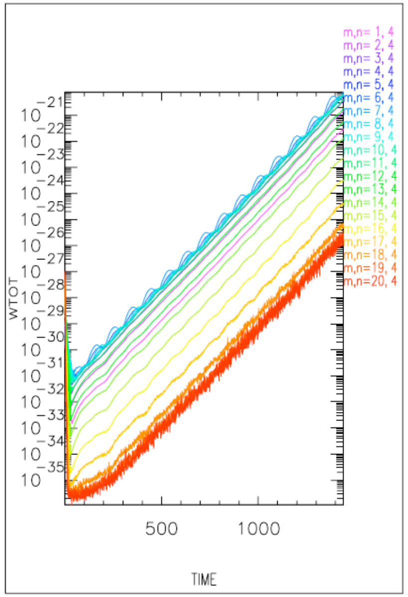
HMGC simulations

- An exponential growth can be observed only for

  ✓ Large drive (the relevant time scale is not that of the radial structure formation, but that of the single-packet growth, shorter than the unperturbed-motion evolution of the distribution function)

  ✓ Small orbit widths (low ρ_α/a): ψ is an almost conserved quantity in the unperturbed motion

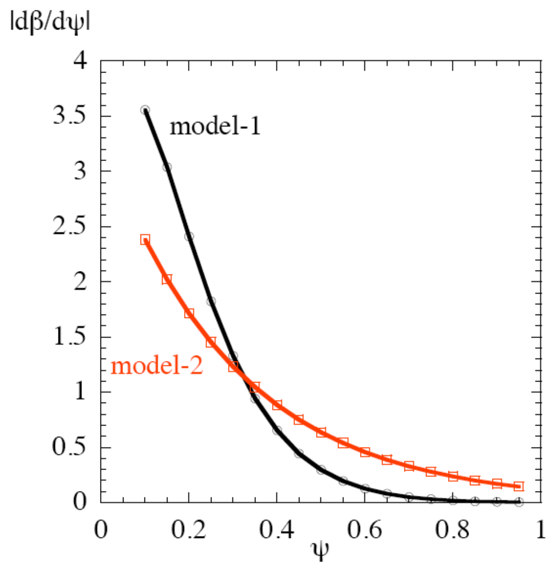




Modified model: equilibrium distribution function

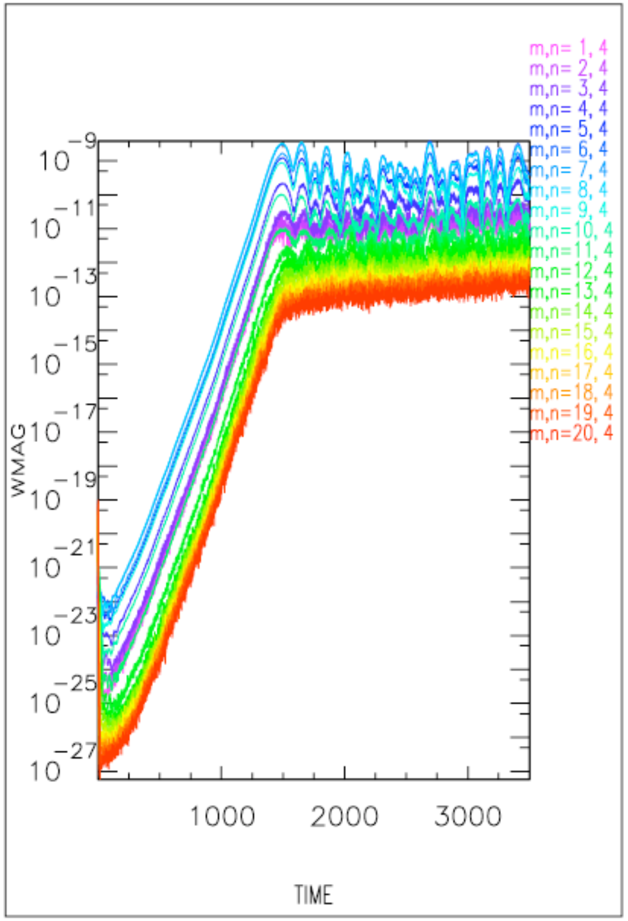
- $n = n_0 \exp(-k\psi) \Rightarrow n_0 \exp(kP_\varphi)$
  with $P_\varphi = -\psi + (mc/q) R v_\varphi$
  ψ dependence in E_{crit} neglected
- Similar models adopted by Fu, Lin, etc.
- Note: arbitrary choice; the linear dependence on P_φ allows use to factorize ψ and velocity dependences
- In general, no unique way to infer the equilibrium distribution function in the phase space from its velocity-space momenta

- k adjusted to yield approximately the same β_E' as the former model at the expected TAE radius: k=3.3



Modified model: equilibrium distribution function

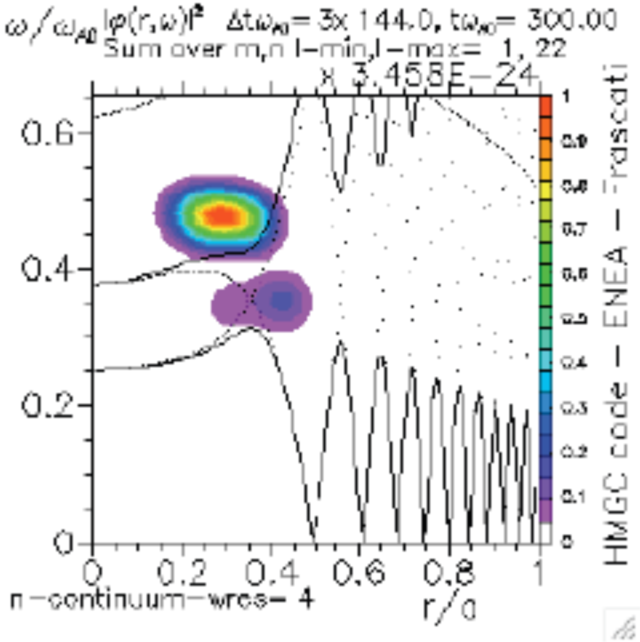
- Exponential growth phase observed, even for low drive

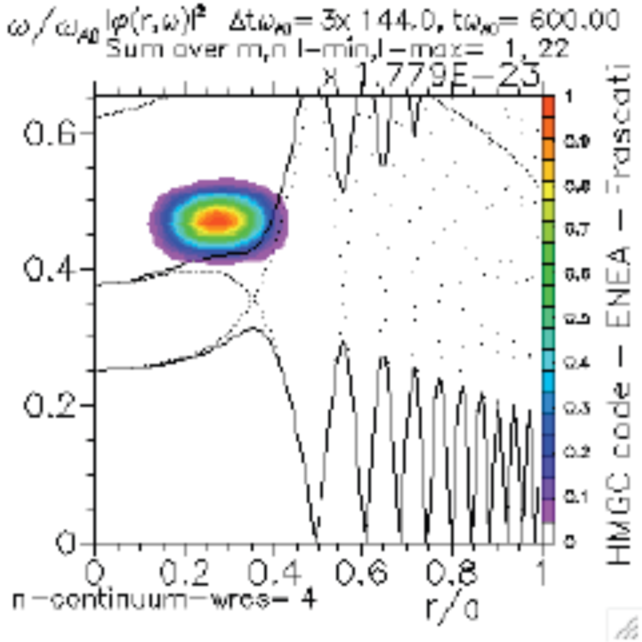


Modified model: linear phase

- Both TAE and KTAE (RPSAE kinetic counterpart) observed at low drive: $(n_\alpha/n_i)_0$=0.014
- KTAE localizes in such a way to minimize continuum damping (that is, where the radial derivative of the continuum frequency is minimum)

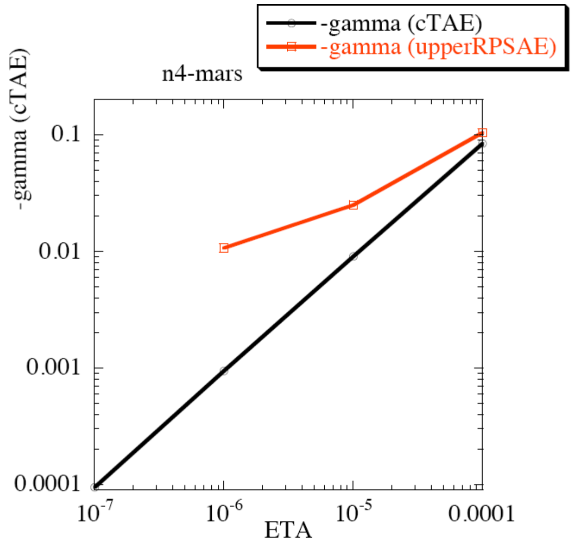
- $(\gamma/\omega)_{KTAE} \sim 0.01$
- $\gamma_{TAE} < \gamma_{KTAE}$ (TAE observable only in the first stage of the linear growth phase)





Modified model: linear phase

- Why does the KTAE dominate?
  - ✓ HMGC is a resistive code
  - ✓ Simulations performed at artificially large resistivity ($S=10^4$) in order to use reasonably large Δt and Δr
  - ✓ In this regime, in the MHD limit (no EP), comparable (significant) damping rates: $\gamma_d^{TAE} \approx \gamma_d^{RPSAE}$
  - ✓ Decreasing η, TAE damping would decrease faster than RPSAE one, yielding
    $$\gamma_d^{TAE} < \gamma_d^{RPSAE}$$
    and, possibly
    $$\gamma_{TAE} > \gamma_{KTAE}$$



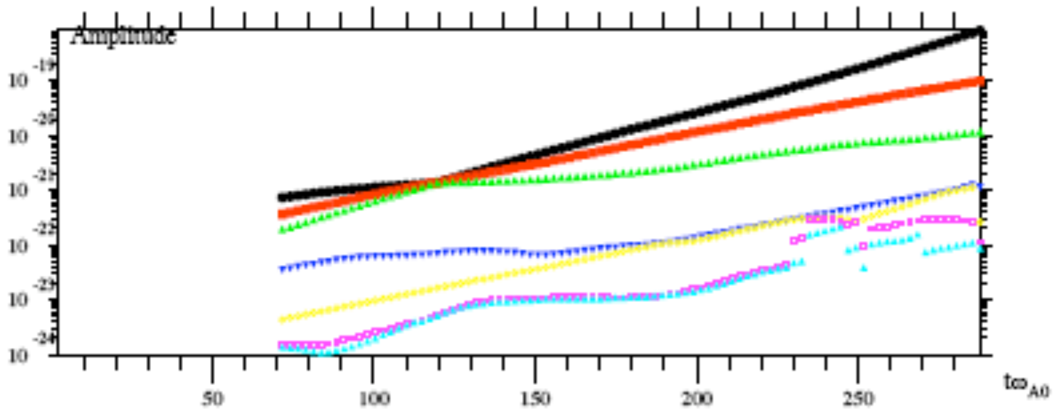
MARS

- Note however that KTAE cannot be analyzed, by a spectral code, as the perturbative modification of a continuum oscillation, whose time behavior is $1/t \exp(-i\omega t)$

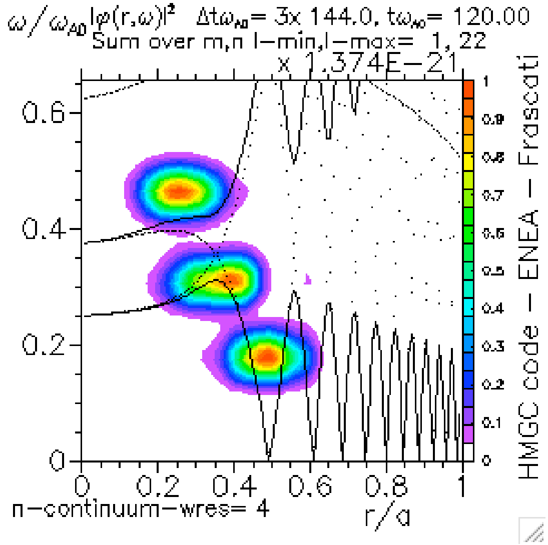
Modified model: linear phase

- Increasing drive, $(n_\alpha/n_i)_0$=0.025:
  - ✓ KTAE and TAE can still be observed
  - ✓ EPM appears

$\gamma_{TAE} \approx 0.006\ \tau_A^{-1}$
$\gamma_{KTAE} \approx 0.019\ \tau_A^{-1}$
$\gamma_{EPM} \approx 0.013\ \tau_A^{-1}$

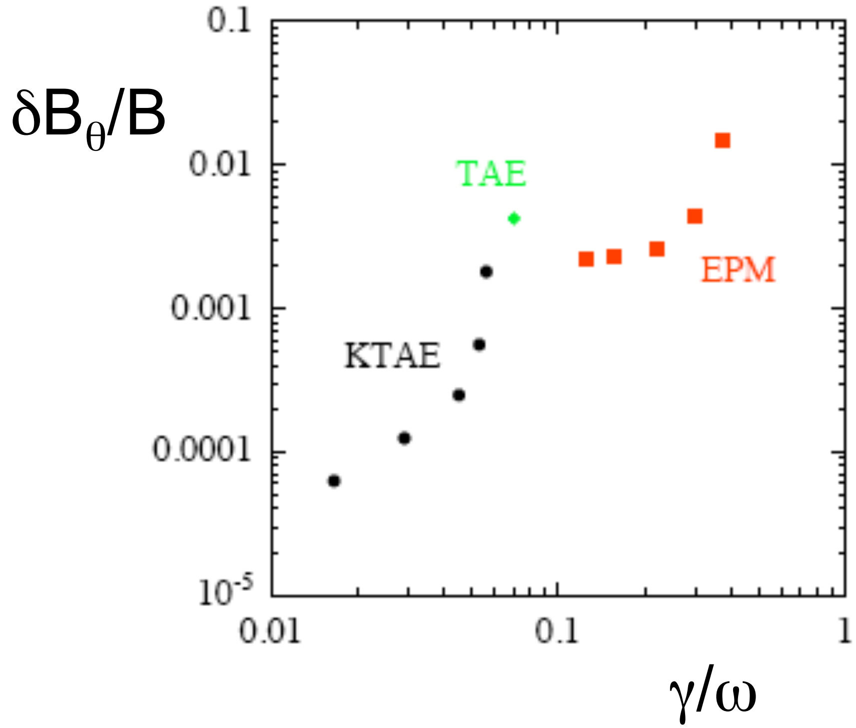


$(\gamma/\omega)_{TAE} \approx 0.02$
$(\gamma/\omega)_{KTAE} \approx 0.045$
$(\gamma/\omega)_{EPM} \approx 0.075$



Modified model: saturation

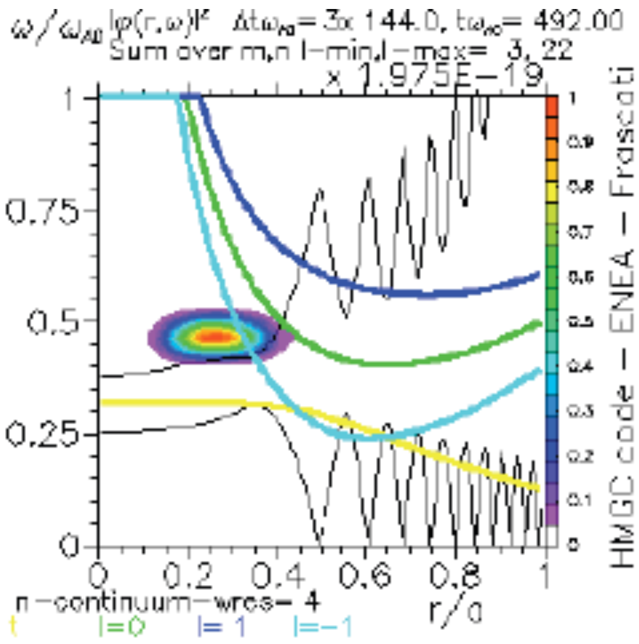
- Different saturation regimes observed for KTAE and EPM
- In the transition regime, both modes coexist with comparable relevance (and TAE as well): possible interference between saturation mechanisms
- Note that the $\delta B_\theta/B$ dependence on γ/ω is different, even for low drive, from the quadratic one usually obtained close to marginal stability



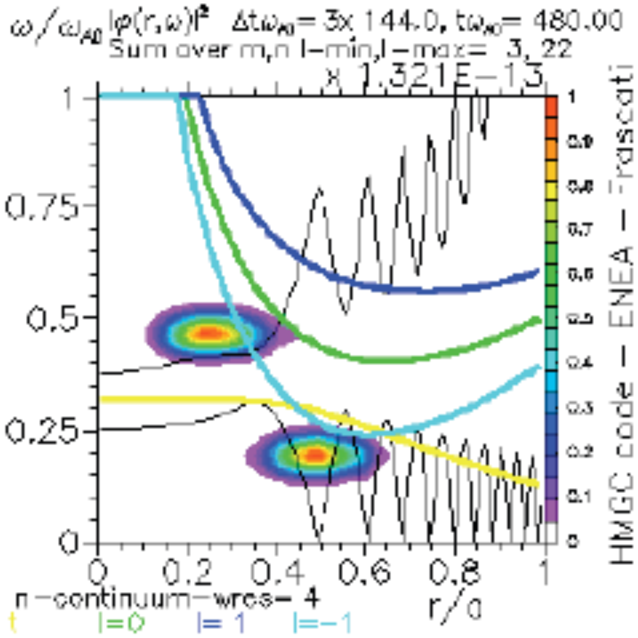
Modified model: saturation

- Saturation mechanisms: comparison between low and high drive regimes

low drive: KTAE

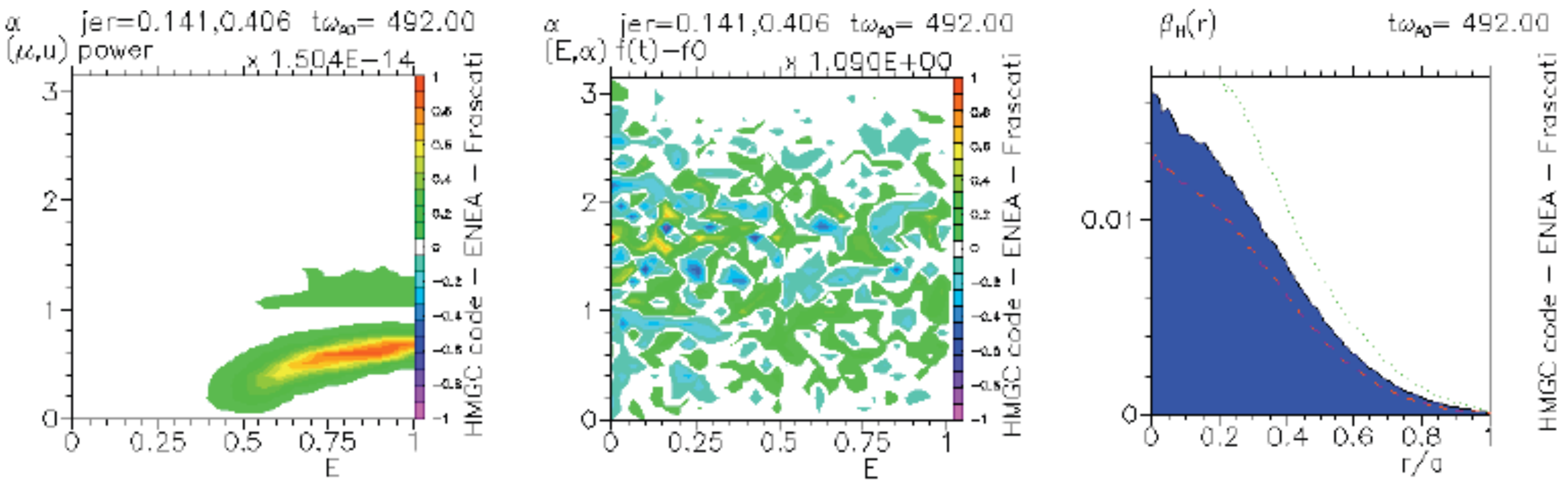


high drive: KTAE and EPM



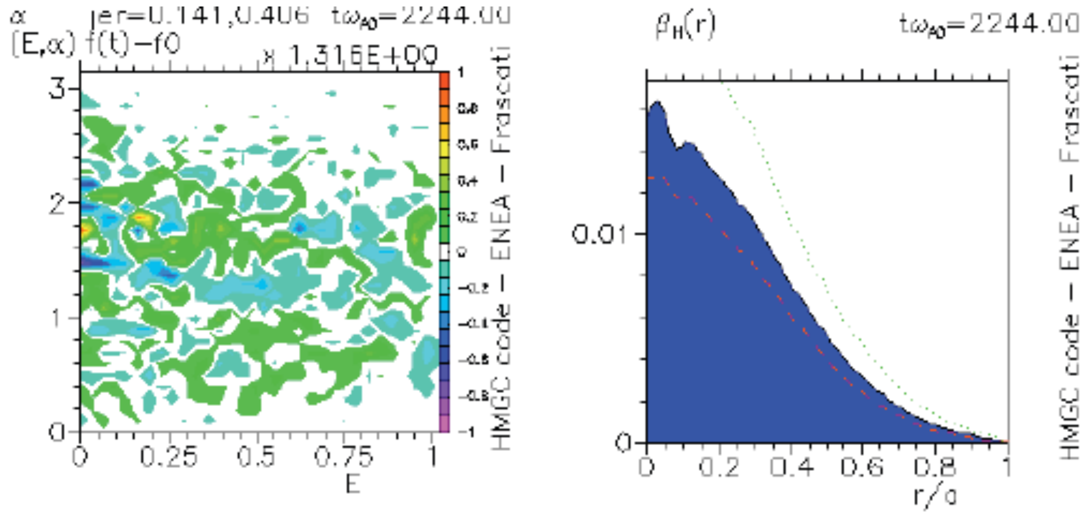
Low drive regime saturation

Power transfer | δF | β_α



Linear phase

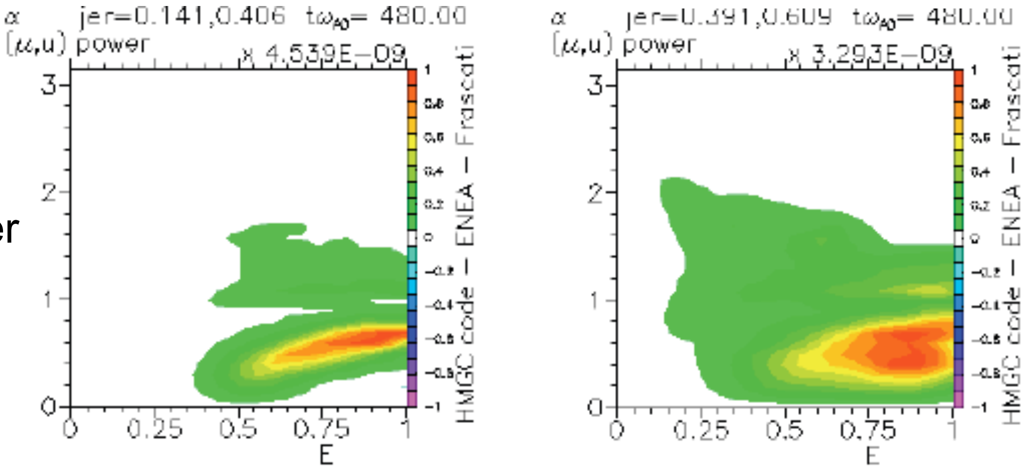
No observable modification in the velocity space distribution function and in the β_α profile



Saturated phase

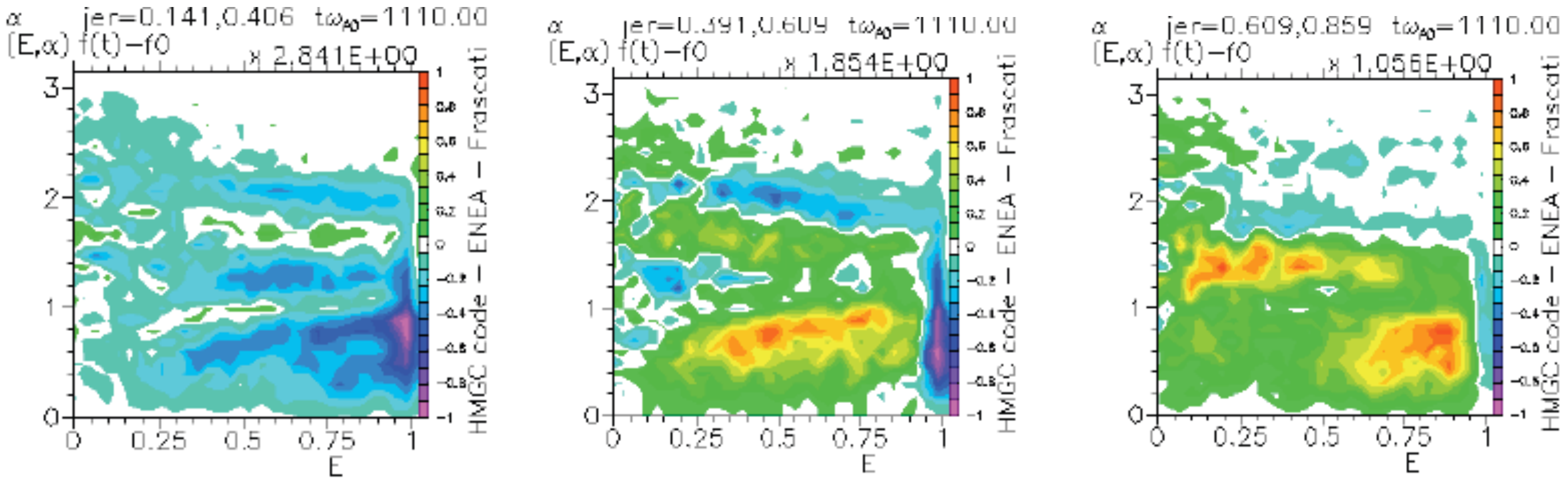
High drive regime saturation

Power transfer



- Resonance region in velocity space is depleted
- Resonant particles are displaced outward

δF



around KTAE | around EPM | outside EPM

Conclusions

- Equilibrium distribution function (function of unperturbed-motion invariants) needed
- Coexistence of TAE, KTAE and EPM observed even in moderate drive regimes
- Different saturation regimes observed in low and high drive limits
  - ✓ in the former, it is hard to detect numerically significant effects on the EP distribution function
  - ✓ in the latter, saturation occurs via an outward radial displacement of resonant particles
- Intrinsic limitations of HMGC: it requires relatively large η and low ε