Global particle-in-cell simulations of Alfvénic modes

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Keywords: gyrokinetic, global particle-in-cell, Alfvén Eigenmodes, fast-particle destabilization, Energetic Particle Modes

Acknowledgments: J. Nührenberg, P. Helander

Role of the fast particles

- **Fusion born fast particles (3.5 MeV), NBI (0.1 MeV), ICRH (1 MeV): characteristic time scales (e.g. transit frequency ω_t) $\sim \omega_{TAE} \Rightarrow$**
  $\Rightarrow$ effective resonant interaction/destabilization

- **Bad news: outward transport of fast particles $\Rightarrow$ non-even heat load on the wall $+$ possible quenching of the fusion reaction**

- **Good news: weak destabilization $\Rightarrow$ MHD spectroscopy,**
  alpha particle channeling (direct transfer the energy of fusion alphas into ions without intermediate step of slowing down on thermal electrons)

ALFVÉN MODE DYNAMICS IS IMPORTANT FOR FUSION

Gyrokinetic Vlasov-Maxwell equations

- **Linearized gyrokinetic Vlasov equation:**

$$\frac{\partial \delta f_s}{\partial t} + \dot{\vec{R}}^{(0)} \cdot \frac{\partial \delta f_s}{\partial \vec{R}} + \dot{v}_{\|}^{(0)} \frac{\partial \delta f_s}{\partial v_{\|}} = -\dot{\vec{R}}^{(1)} \cdot \frac{\partial F_{0s}}{\partial \vec{R}} - \dot{v}_{\|}^{(1)} \frac{\partial F_{0s}}{\partial v_{\|}}$$

- **Gyrocenter equations of motion ($p_{\|}$-formulation):**

$$\dot{\vec{R}} = \left(v_{\|} - \frac{q}{m} \langle A_{\|} \rangle \right) \vec{b}^* + \frac{1}{q B_{\|}^*} \vec{b} \times \left[\mu \nabla B + q \left(\nabla \langle \phi \rangle - v_{\|} \nabla \langle A_{\|} \rangle \right) \right]$$

$$\dot{v}_{\|} = -\frac{1}{m} \left[\mu \nabla B + q \left(\nabla \langle \phi \rangle - v_{\|} \nabla \langle A_{\|} \rangle \right) \right] \cdot \vec{b}^*$$

- **The gyro-averaged potentials are defined as usual:**

$$\langle \phi \rangle = \oint \frac{\mathrm{d}\theta}{2\pi} \phi(\vec{R} + \rho) \; , \quad \langle A_{\|} \rangle = \oint \frac{\mathrm{d}\theta}{2\pi} A_{\|}(\vec{R} + \rho)$$

Gyrokinetic Vlasov-Maxwell equations

- **Gyrokinetic quasineutrality equation and parallel Ampére's law ($p_\|$-formulation):**

$$-\nabla\cdot\left[\left(\sum_{s=i,f}\frac{q_s^2 n_s}{T_s}\rho_s^2\right)\nabla_\perp\phi\right]=\sum_{s=i,e,f} q_s\delta n_s$$

$$\left(\sum_{s=i,e,f}\frac{\hat{\beta}_s}{\rho_s^2}-\nabla_\perp^2\right)A_\| = \mu_0\sum_{s=i,e,f}\delta j_{\|s}$$

- **The gyrocenter perturbed density and current:**

$$\delta n_s=\int \mathrm{d}^6 Z\,\delta f_s\,\delta(\vec{R}+\rho-\vec{x})\ ,\quad \delta j_{\|s}=q_s\int \mathrm{d}^6 Z\,\delta f_s\,v_\|\,\delta(\vec{R}+\rho-\vec{x})$$

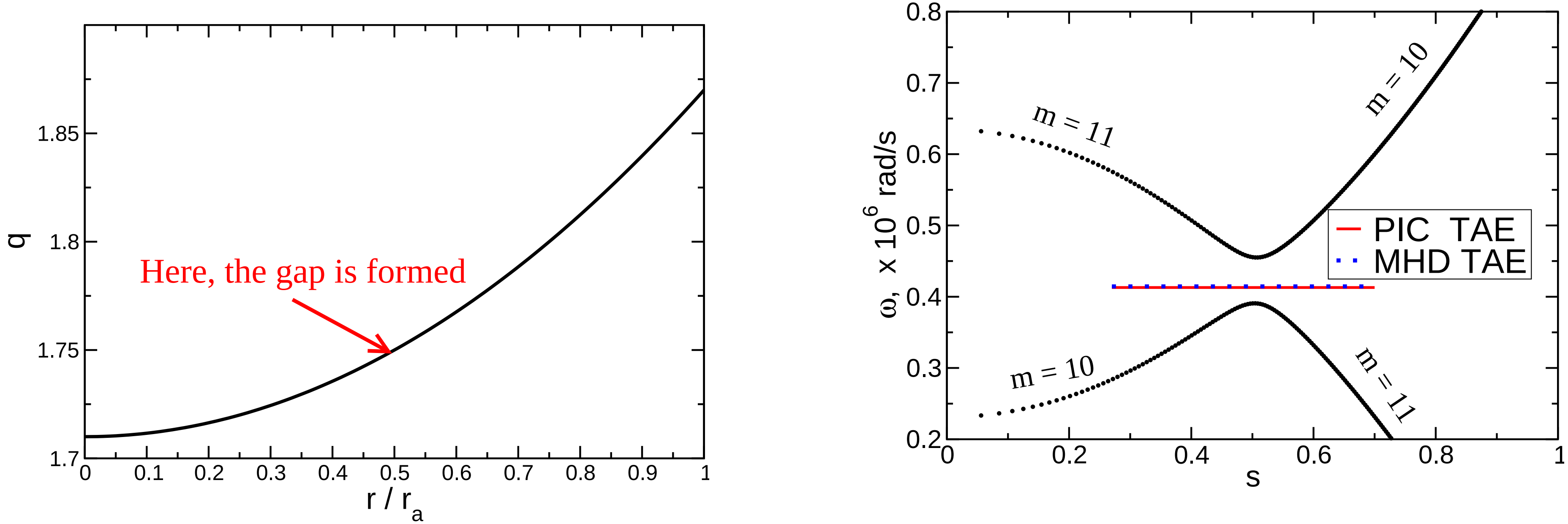
- **The background densities satisfy the quasineutrality equation**

$$\sum_{s=i,e,f} q_s n_s = 0$$

Numerical approach

- linear δf- particle-in-cell (PIC) method
- field discretization using B-splines
- phase factor transform
- Fourier transform in the direction of symmetry
- most serious numerical problem to solve for electromagnetic calculations: cancellation problem
- iterative solution of Ampere's law to cancel unphysical "adiabatic currents"
  detailed description:
  R. Hatzky, A. Könies, and A. Mishchenko, J. Comp. Phys. 255, 568 (2007)
  Similar to Y. Chen and S. Parker approach
- Performance optimization: parallel efficiency 97%, 4096 cores, Blue Gene/P (weak scaling)

Tokamak configuration



Large-aspect-ratio, circular cross-sections

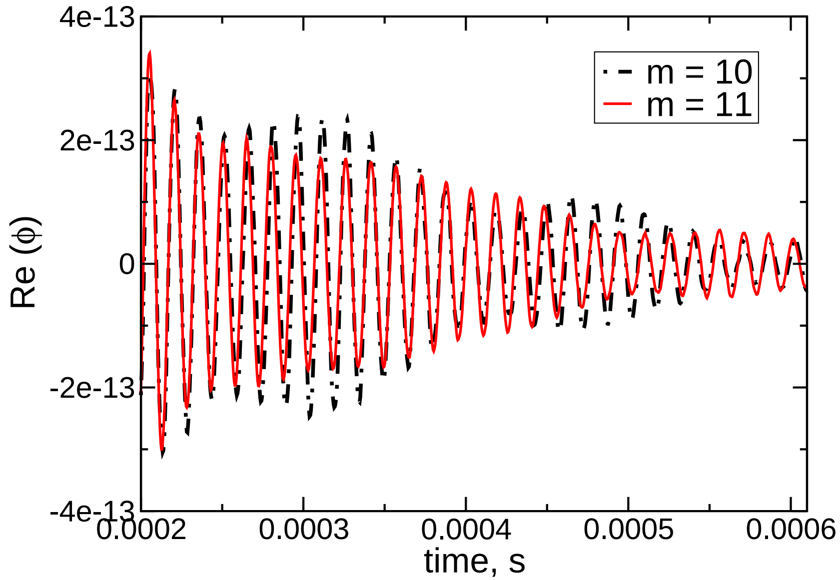
Major radius $R_0 = 10$ m, minor radius $r_a = 1$ m

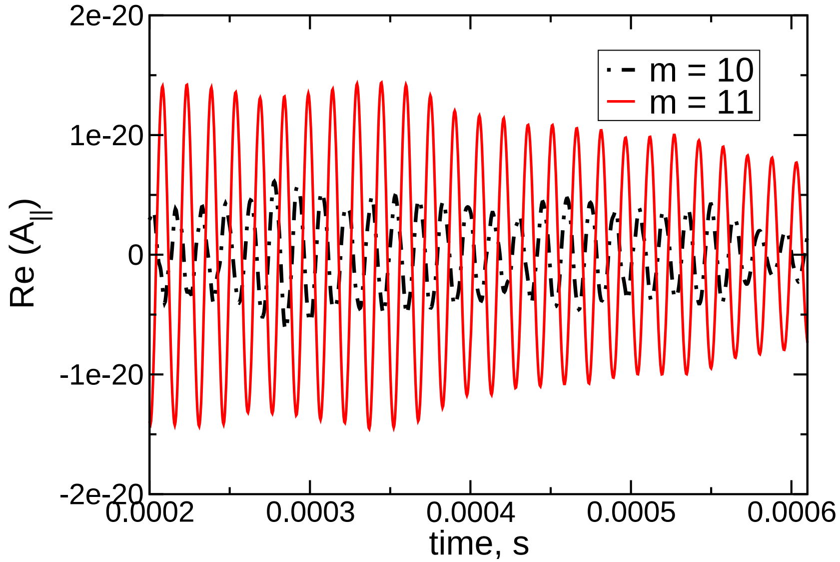
Magnetic field on the axis $B_0 = 3.0$ T,

Flat bulk-plasma temperature and density ($\beta_{\text{bulk}} \approx 0.18\%$)

Toroidal mode number $n = 6$

Time signal

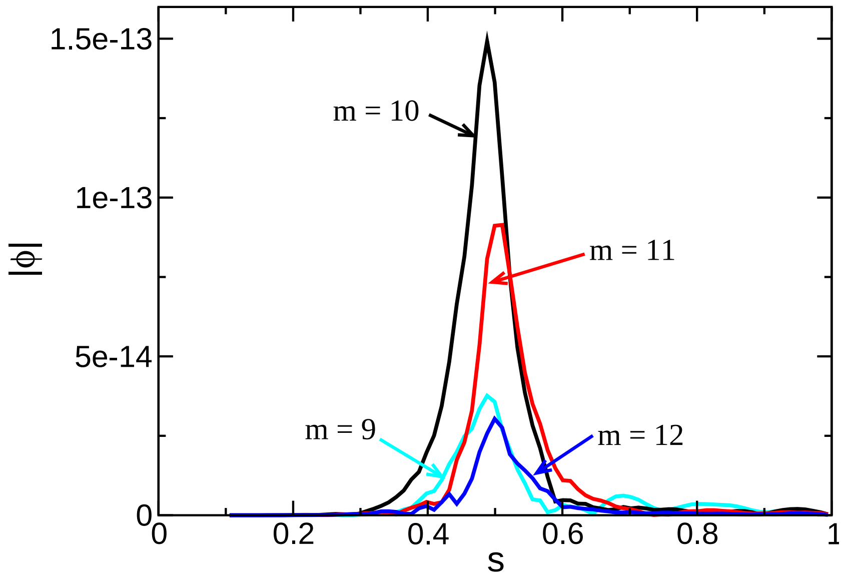


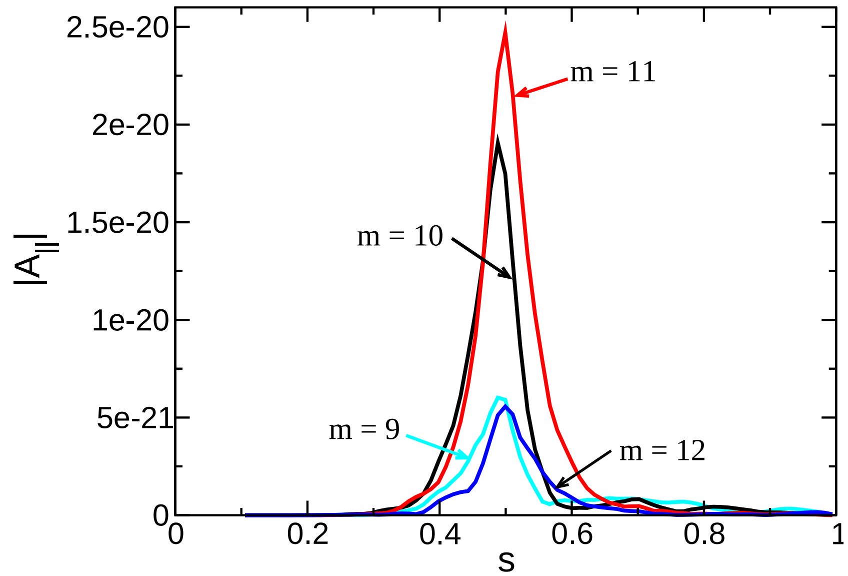


Time signal resulting from the PIC simulations.

Dominant harmonics in ϕ have the same phase.
Dominant harmonics in $A_{||}$ have the opposite phase.
This corresponds to the property $E_{||} \approx 0$.

Radial structure

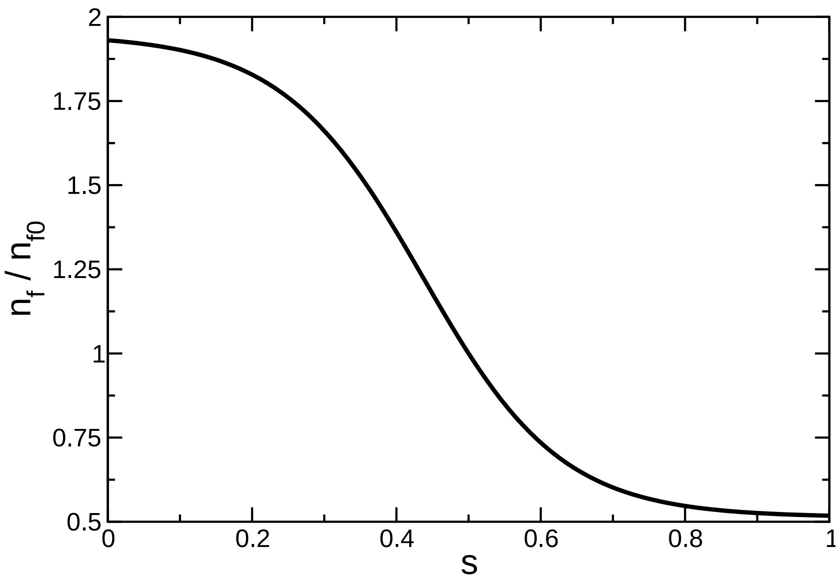


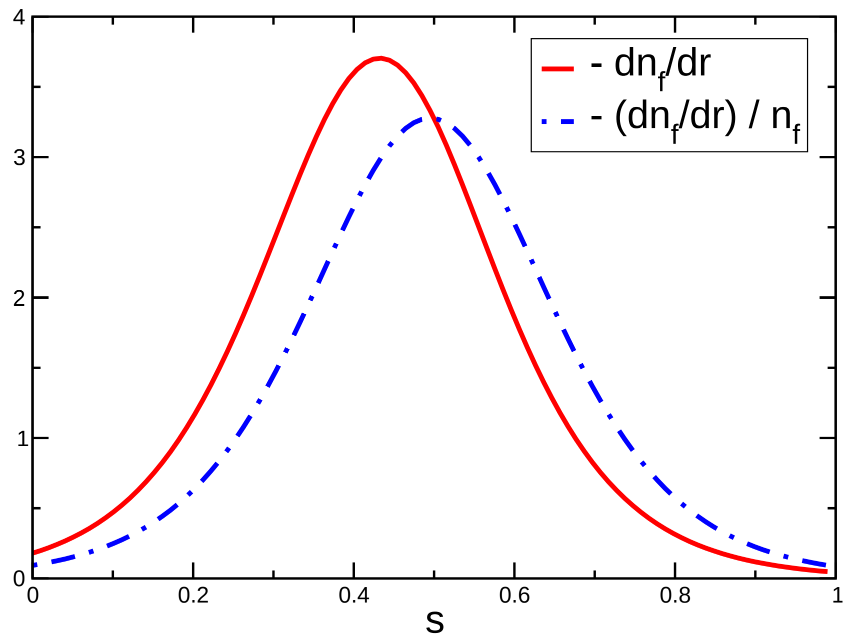


Radial pattern resulting from the PIC simulations
(in some particular point of time)

It resembles a typical TAE structure.

The fast-particle profiles



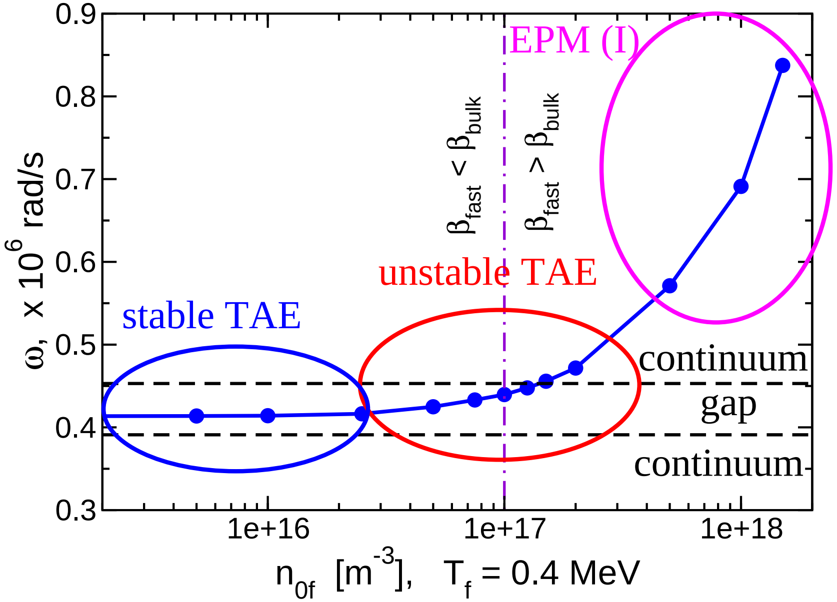


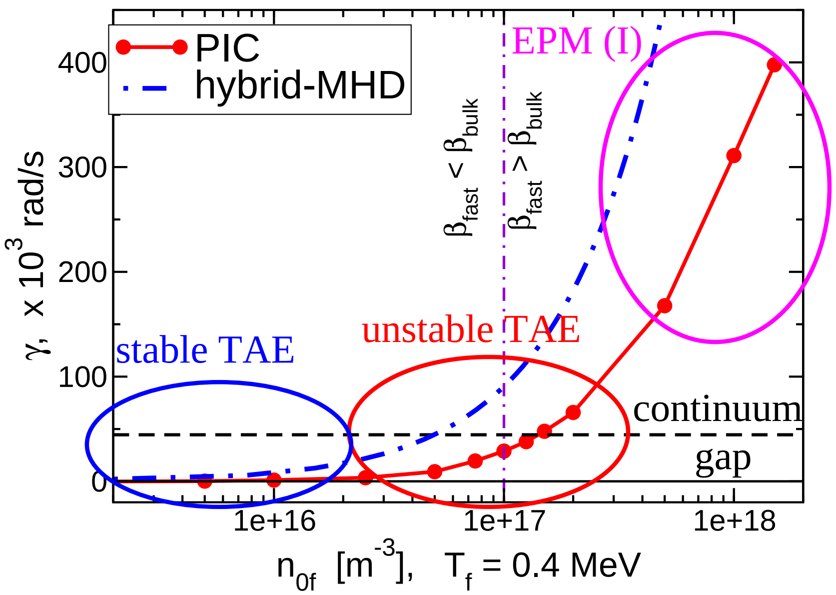
Nonuniform fast-particle density is used to drive the modes

Position of max. $\mathrm{d}\ln n_f/\mathrm{d}r$ **coincides with the position of the gap**

The fast-particle temperature is flat

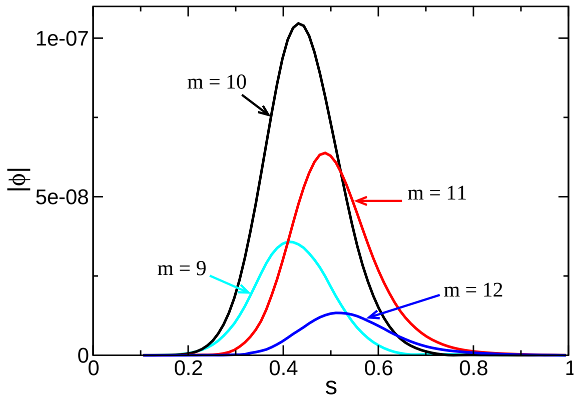
Fast-particle density sweep

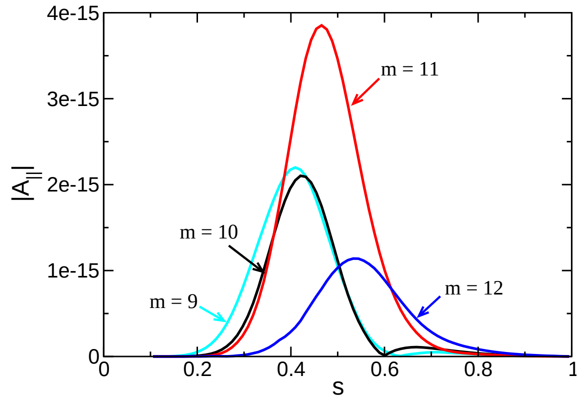




TAE destabilized by fast particles. It is continuously modified into EPM as the drive increases.
Hybrid-MHD calculations (CAS3D-K) overestimate the growth rate (FLR and FOW are neglected in CAS3D-K)

Energetic Particle Mode (Type I)



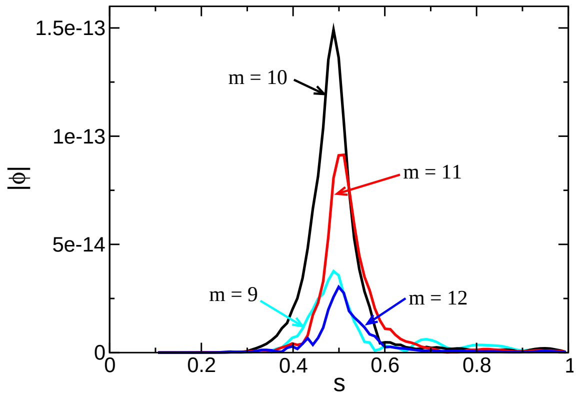


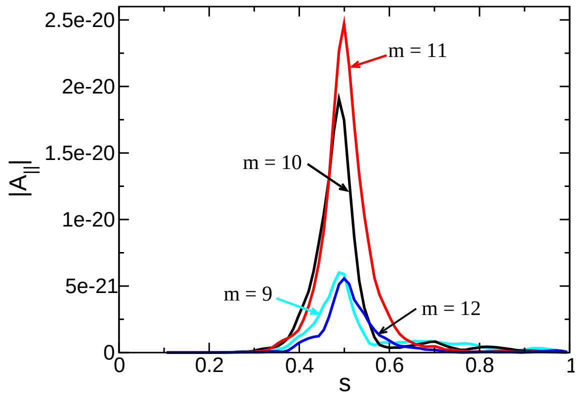
EPM (Type I)

$\beta_f \approx 1.8\%$

$n_f = 10^{18}\ m^{-3}$

$T_f = 0.4\ MeV$

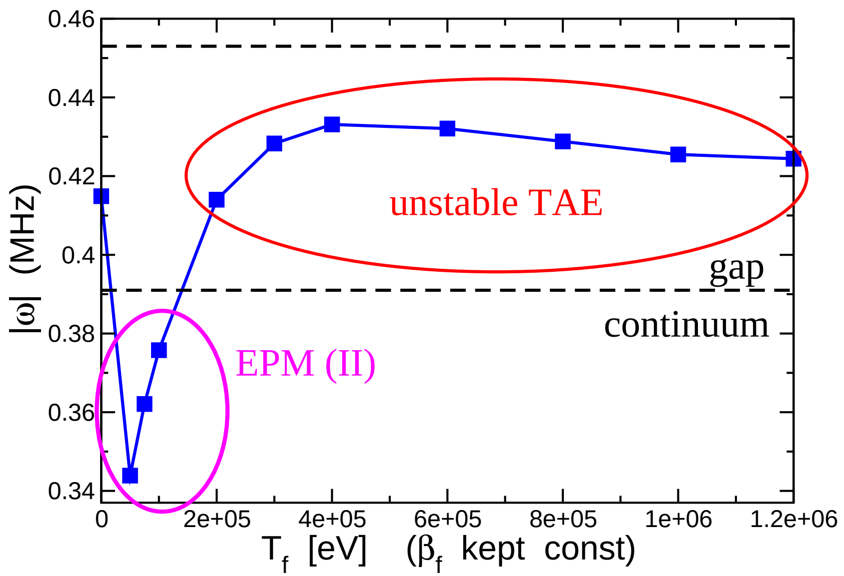


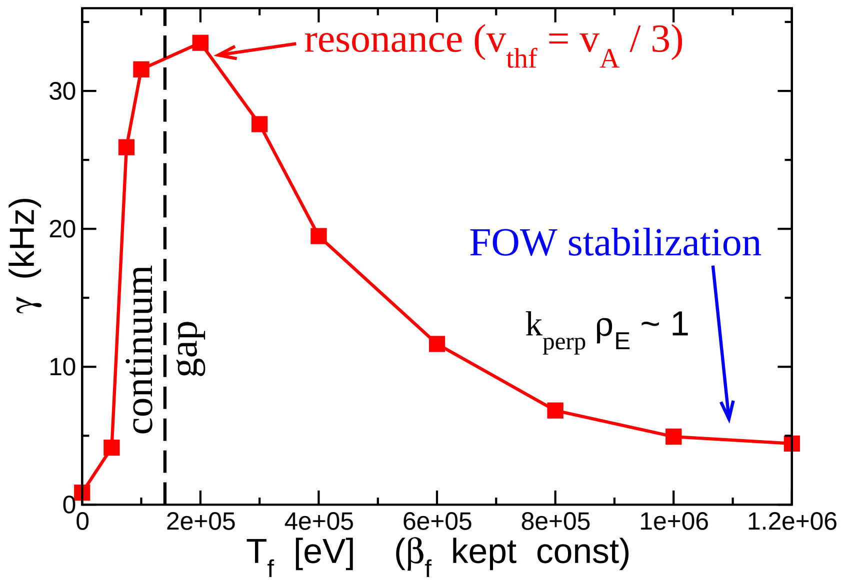


stable TAE
(no fast particles)

$\beta_f = 0$

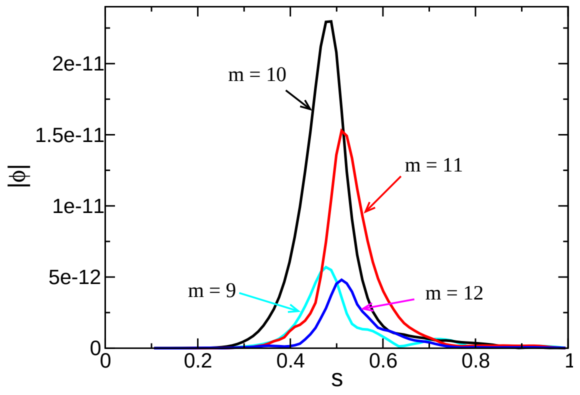
Fast-particle temperature sweep (I)

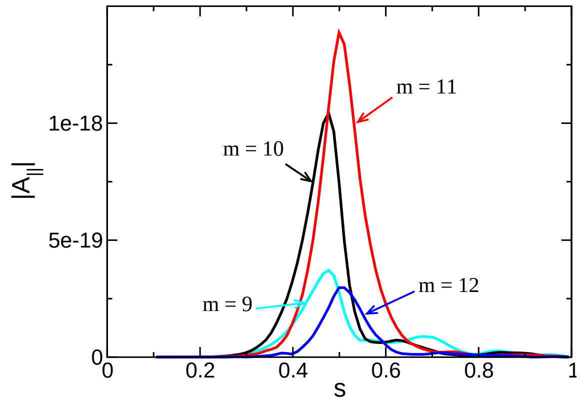




Dependency on the fast-particle temperature ($\beta_f = 0.134\%$ kept constant)
Destabilization is most effective near the resonance $v_{thf} \approx v_A/3$
At large T_f, finite-orbit-width (FOW) stabilization is seen
At smaller T_f (larger n_f to keep β_f constant), an EPM appears

Unstable Toroidal Alfvén Eigenmode



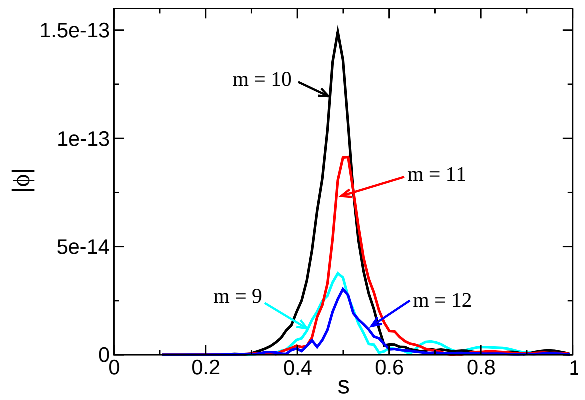


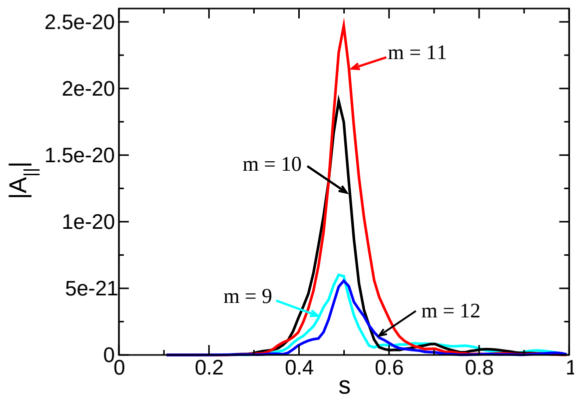
unstable TAE

$\beta_f \approx 0.134\%$

$n_f = 0.5 \times 10^{17}\ m^{-3}$

$T_f = 0.6\ MeV$



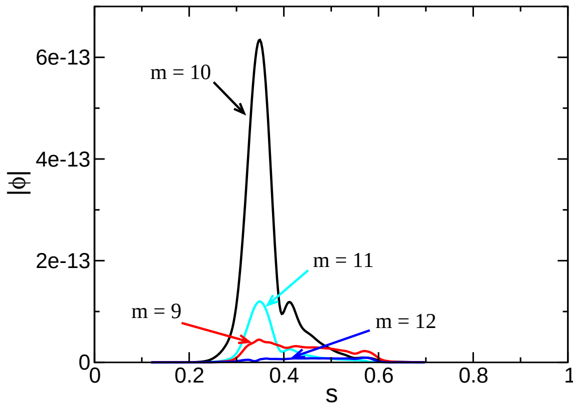


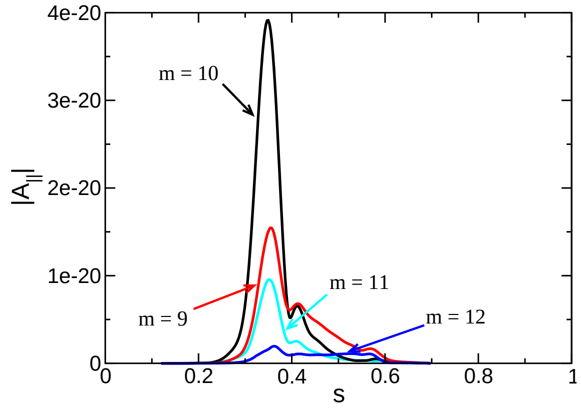
stable TAE

(no fast particles)

$\beta_f = 0$

Energetic Particle Mode (Type II)



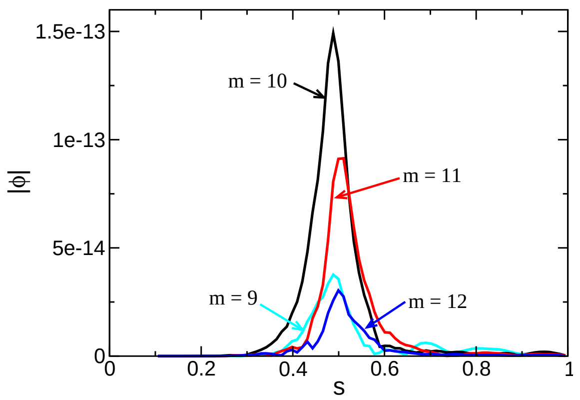


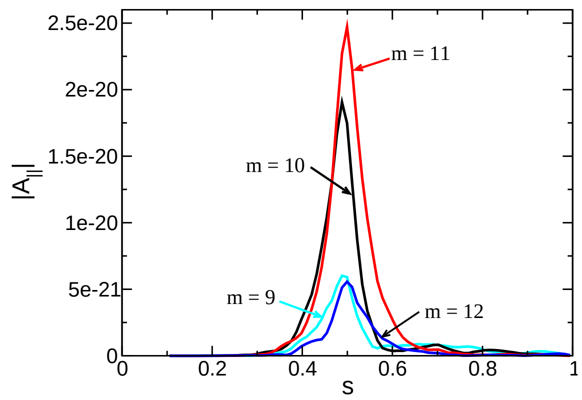
EPM (Type II)

$\beta_f \approx 0.134\%$

$n_f = 6 \times 10^{17}\ m^{-3}$

$T_f = 0.05\ MeV$



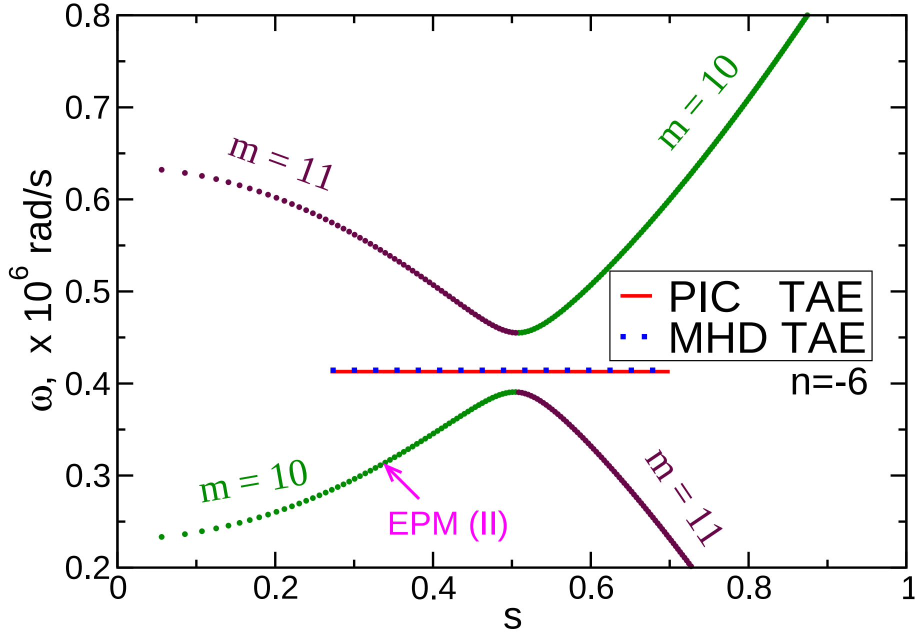


stable TAE

(no fast particles)

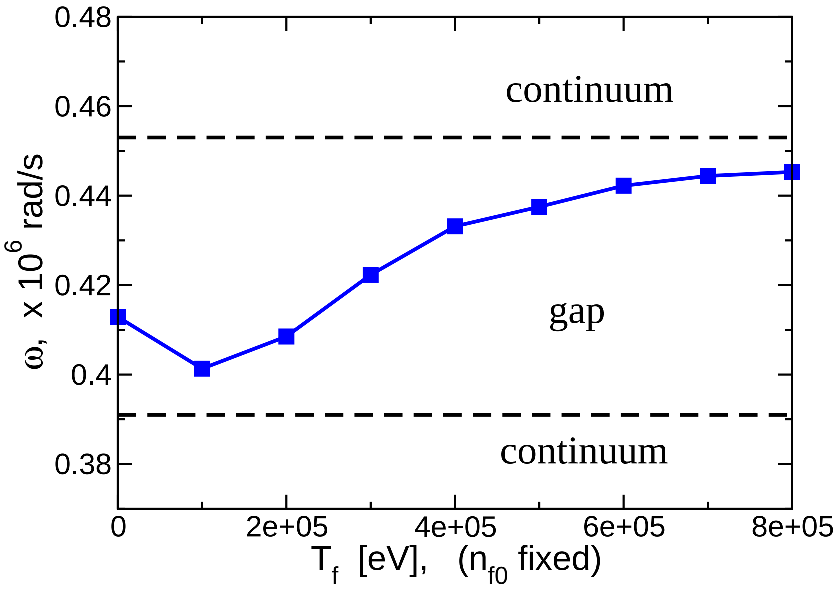
$\beta_f = 0$

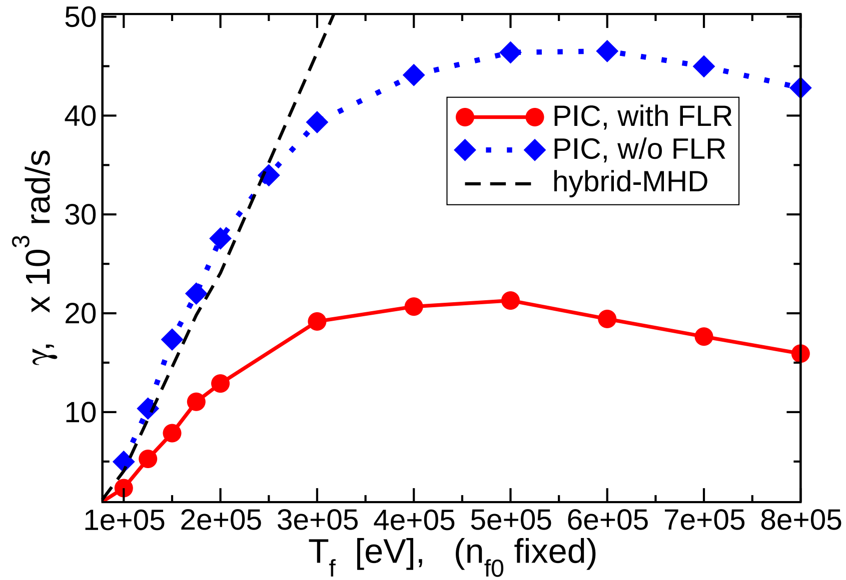
Energetic Particle Mode (Type II)



Location and frequency of the EPM mode are determined by continuum

Fast-particle temperature sweep (II)





The fast-particle density $n_f = 0.75 \times 10^{17}\ m^{-3}$ is kept constant
The mode frequency remains in the gap (no modification into the EPM)
At larger temperature, FOW stabilization can be seen

Fast particles. Unstable Alfvén modes. Summary.

- **Fast-particle destabilization of the TAE modes has been modelled with PIC code**
- **A transformation of the TAE mode into the EPM instability if the drive is large enough has been observed**
- **Next steps**
  - **Benchmarking: <u>ORB5</u>, <u>LIGKA</u>, GENE (global), GTC (?)**
  - **Numerical equilibria, smaller aspect ratio (more reactor-like)**

Global particle-in-cell simulations of Alfvénic modes

- **Alfvén-sound couplings (BAE . . .), Alfvén cascades**
- **Kink mode, microtearing mode**
- **Nonlinear effects**
  - **nonlinear TAE/EPM phase-space dynamics (avalanches, spontaneous hole-clump pair creation, etc)**
  - **nonlinear TAE-EPM saturation**
- **Alfvén Eigenmodes + fast particles in stellarators (MAE, GAE, HAE etc)**