Benchmark of the HYMAGYC code
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Outline
- The hybrid MHD-Gyrokinetic model has been proven very successful in describing the interaction between Alfvén waves and energetic particles in toroidal devices.
- Numerical codes using this approach have been used to study linear and nonlinear dynamics of TAEs, EPMs, BAEs, (c)-fishbones, etc.
- The application of hybrid codes to study the behaviour of these modes in present experiments or future ignited devices, makes necessary the developing of more refined numerical tools.

From present Frascati hybrid MHD-gyrokinetic code: HMGCG...

- Thermal (core) plasma:
  - described by reduced $O(e^2)$ visco-resistive MHD equations in the limit of zero pressure ($\varepsilon = aR_p$ being the inverse aspect ratio of the torus; this model allows to investigate equilibria with shifted circular magnetic surfaces only)
  - MHD fields, low-$\beta$ limit: $\phi$ (poloidal flux function), $\phi$ (scalar potential)
- Energetic-ion population:
  - described by the nonlinear gyrokinetic Vlasov equation, with equations of motion expanded up to order $O(\varepsilon)$ and $O(\varepsilon^2)$ (with $\varepsilon$, $\delta\gamma$, $L_{\parallel}$ and $\delta\gamma_{\parallel}L_{\parallel}$),
  - guiding-center approximation $\varepsilon$, $\delta\gamma_{\parallel}L_{\parallel}$,<1, (but magnetic drift orbit widths fully retained),
  - energetic particle pressure: $H^i_\perp$, $\Pi_{\parallel}$
  - solved by particle-in-cell (PIC) techniques.
- Coordinates system ($r$, $\chi$, $\phi$)

Analytic energetic particle response compared with HYMAGYC and HMGCG, assuming:

(a) unperturbed particle motion
(b) no mirroring term in the parallel velocity equation
(c) no relaxation term of the energetic part. initial non-equilibrium dist. function in the linearized Vlasov equation
(d) large aspect ratio $aR_0 <<1$
(e) circular magnetic flux surfaces
(f) flat $\rho$ profile
(g) circulating energetic particles with $p_\parallel a <<1$
(h) electromagnetic fields with scalar potential $\delta\gamma$ and vector potential $\delta\gamma_\perp << \delta\gamma_\parallel$

Unperturbed orbits in the (R,Z) plane for a JET-like equilibrium

- Circulating particles (yellow, red)
- Trapped particles (green, blue, magenta, cyan)

Simulations using complete versions of HMGCG and HYMAGYC (i.e., self-consistent evolution of fields and energetic particles), $n=2$, $m=1,...,4$

HYMAGYC and HMGCG comparison, relaxing some of the previous restrictions (no analytical solution available):

(a) perturbed particle motion
(b) mirroring term in the parallel velocity equation
(c) relaxation term of the energetic part. initial non-equilibrium dist. function in the linearized Vlasov equation
(d) large aspect ratio $aR_0 <<1$
(e) circular magnetic flux surfaces
(f) flat $\rho$ profile
(g) circulating energetic particles with $p_\parallel a <<1$
(h) electromagnetic fields with scalar potential $\delta\gamma$ and vector potential $\delta\gamma_\perp << \delta\gamma_\parallel$