From present Frascati hybrid MHD-Gyrokinetic code: HMGC...

• Thermal (core) plasma:
  - described by reduced $O((\varepsilon))^2$ visco-resistive MHD equations in the limit of zero pressure ($\varepsilon = a/R_c$ being the inverse aspect ratio of the torus; this model allows to investigate equilibria with shifted circular magnetic surfaces only).

• MHD fields: $\phi$ (poloidal flux function), $\rho$ (e.s. potential).

• Energetic-ion population:
  - described by the nonlinear gyrokinetic Vlasov equation, expanded up to order $2\varepsilon$ of the equilibrium linearization of the potential

- performs a gauge transformation of the magnetic fields: $A^\rho \to A^\rho + (\varepsilon \phi A^\phi)$, with $\phi$ the equilibrium potential.

• MHD-Gyrokinetic module: origins from the code MARS:
  - quantities required by stability codes
  - CHEASE code solves the Grad-Shafranov equilibrium equations
  - performs a gauge transformation of the equilibrium field gradients.

- solves the linearized MHD equations in arbitrary curvilinear geometry.

- The MHD module is an initial-value version of the original MARS, with $\rho_c$ being the equilibrium ion Larmor radius and $L_\phi$ the equilibrium magnetic field scale length, and in the $k_B T_e$/c $<<$ limit (with $k_B$ the component of the wave vector perpendicular to the magnetic field)

- energetic particle pressure: $\Pi_\rho$, $\Pi_\phi$

- magnetic drift orbit widths fully retained,

- solved by particle-in-cell (PIC) techniques.

- Coordinates system $(r, \theta, \phi)$

- Equilibrium Interface Module
  - Prepare boundary conditions
  - reads equilibrium quantities (provided by CHEASE and by the equilibrium interface module)
  - initializes the particle gyrocenter coordinates
  - performs s-p or p-s transition

- At any time step:
  - computes scalar fields defined on the gyrokinetic grid and which contain only equilibrium quantities (computed at $\varepsilon = 0$)

MHD-Gyrokinetic interface

- The interface between MHD and GK modules:
  - performs a gauge transformation of $\rho$ and $A$ computed by the MHD module in order to regularize the solution toward the magnetic axis
  - provides Fourier anti-transforms in the generalized poloidal angle for several fields ($A^\rho \to A^\rho + (\varepsilon \phi A^\phi)$)

- computes $\bar{\rho}$, $\bar{A^\rho}$, $\bar{A^\phi}$ of $\rho$ and $A$ using cubic splines

- the gyrokinetic averaged gyrocenter pressure tensor terms added to the fluid momentum equation

HMF module originates from the code MARS:

- Fourier decomposition in $(r, \theta, \phi)$ space, to solve the MHD linear equations

- the magnetic moment and the parallel velocity

- at any time step: performs s-p or p-s transition

- computes the scalar fields defined on the $(r, \theta, \phi)$ grid which depend on the perturbed electromagnetic fields

- Particle pushing

- Gyrokinetic module:

P-playing role of the equilibrium field gradients

- launches particle gyrocenter coordinates

- performs s-p or p-s transition

- computes scalar fields defined on the $(r, \theta, \phi)$ grid which depend on the perturbed electromagnetic fields

- Equilibrium Interface Module

- At any time step:
  - computes scalar fields defined on the gyrokinetic grid and which contain only equilibrium quantities (computed at $\varepsilon = 0$)

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Outline

• A new hybrid MHD-gyrokinetic code has been developed for the simulation of the nonlinear interactions between Alfvén modes and energetic ions.

• Different from HMGC [1], the new code is suited for studying general axisymmetric high-$\varepsilon$ equilibria (and, thus, fully retaining perturbed electromagnetic fields).

• The gyrokinetic ordering, $\varepsilon = \varepsilon_B$ (with $\varepsilon_B$ being the perpendicular wave vector of the fluctuations and $\varepsilon_B$ the ion Larmor radius, respectively), is also assumed. The energetic ion dynamics is obtained by solving the gyrokinetic equations of motion expanded up to the order $O(\varepsilon^2)$ and $O(\varepsilon^3)$, with $\phi$ being the gyrokinetic ordering parameter $(\varepsilon \phi \phi_0 \phi_0^0)$, $\varepsilon_B$ the equilibrium density scale length and $\varepsilon_B/2\varepsilon$ the ratio between the ion Larmor radius and the equilibrium magnetic field scale length.

• Two main modules constitute the core of the new hybrid code: a MHD module and a Gyrokinetic one.

• The MHD module is an initial-value version of the original MARS [2, 3] (adapted for the computation of the perturbed scalar and vector potentials, besides the perturbed magnetic and velocity fields), and solves the linear, full MHD equations in arbitrary curvilinear geometry.

• The Gyrokinetic module solves the nonlinear gyrokinetic Vlasov equation for the fast ion population by particle-in-cell techniques, yielding the fast ion pressure tensor back to the MHD solver to close the hybrid system [5].

• Several equilibrium quantities specifically required by the Gyrokinetic module, besides the standard output already provided for the MARS code, have been obtained by a modified version of the CHEASE [4] code, and suitably elaborated in order to obtain the desired objects (e.g., the Christoffel symbols).

• The MHD module originates from the code MARS:
  - performs a gauge transformation of the magnetic fields; $A^\rho \to A^\rho + (\varepsilon \phi A^\phi)$, with $\phi$ the equilibrium ion Larmor radius and $L_\phi$ the equilibrium magnetic field scale length, and in the $k_B T_e$/c $<<$ limit (with $k_B$ the component of the wave vector perpendicular to the magnetic field).
  - energetic particle pressure: $\Pi_\rho$, $\Pi_\phi$.
  - magnetic drift orbit widths fully retained.
  - solved by particle-in-cell (PIC) techniques.
  - Coordinates system $(r, \theta, \phi)$.

- Fourier transforms pressure tensor:
  - Fourier anti-transforms MHD fields:
  - computes derivative fields of $\Phi$, $B$, $A$.

- Fourier transforms pressure tensor: $(\Pi^\Pi_\rho)^{(m,n)}$, $\Pi^\Pi_\phi$, $\Pi^\Pi_\theta$, $\Pi^\Pi_\phi$, $\Pi^\Pi_\theta$, $\Pi^\Pi_\phi$.

- MHD-Gyrokinetic Interface

- at $t = 0$: initialize simulation particles.
  - computes scalar fields with pert. quantities
  - pushes particles
  - computes $(\Pi^\Pi_\rho)^{(m,n)}$.

- Gyrokinetic module:

- at $t = 0$: initialize simulation particles.
  - computes scalar fields with pert. quantities
  - pushes particles
  - computes $(\Pi^\Pi_\rho)^{(m,n)}$.

- Equilibrium Interface Module

- Prepare boundary conditions
  - reads equilibrium quantities (provided by CHEASE and by the equilibrium interface module)
  - initializes the particle gyrocenter coordinates
  - performs s-p or p-s transition

- at any time step:
  - computes the scalar fields defined on the gyrokinetic grid and which contain only equilibrium quantities (computed at $\varepsilon = 0$)

- Particle pushing

- Gyrokinetic module:

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Toward a New Hybrid MHD Gyrokinetic Code: Progresses and Perspectives

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CHEASE circular shape, $\varepsilon_0 = 0.1$

Gyrokinetic module (unperturbed orbits)

Equilibrium Interface Module [equilibrium scalar $(\mathbf{v}, \varepsilon_1)$]

MARST - TAE

MARST - Internal kink

Gyrokinetic module (up perturbed orbits)