EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT
Task Force
INTEGRATED TOKAMAK MODELLING

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Hybrid MHD-Gyrokinetic codes for studying the mutual nonlinear interaction of shear Alfvén modes and energetic particles

Presented by G. Vlad

on behalf of S. Briguglio, C. Di Troia, G. Fogaccia, F. Zonca
Associazione Euratom-ENEA sulla Fusione, Frascati

TF Leader : P. Strand,
Deputies: R. Coelho, L-G. Eriksson, G. Falchetto

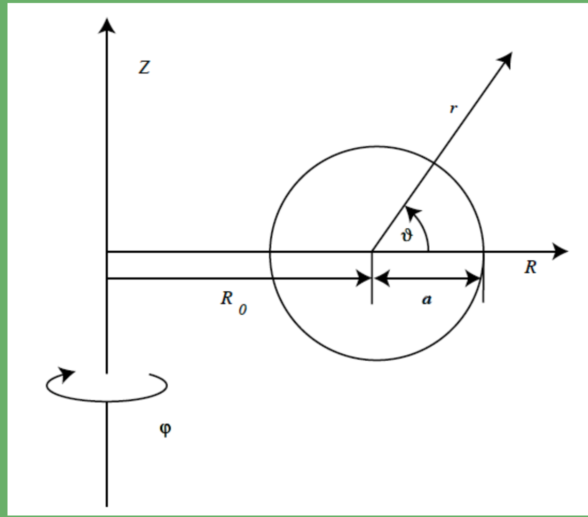
EFDA CSU Contact Person: D. Kalupin

Energetic particle activities

- WP10-ITM-IMP5-ACT5: HMGC

–Status and recent developments of HMGC:

HMGC



- Routinely runs on the Gateway as a stand-alone module
- Description of initial fast particle distribution function in the space of constant of motion
- The new version of HMGC can have two species of kinetic particles with different (anisotropic) initial distribution functions (e.g., slowing down (NBI, alphas) and bi-Maxwellian (ICRH))
- Added thermal ion compressibility and diamagnetic effects in addition to EP kinetic behaviours (eXtended HMGC, XHMGC)

–Deliverables before end 2010:

- A simple interface to equilibrium CPOs

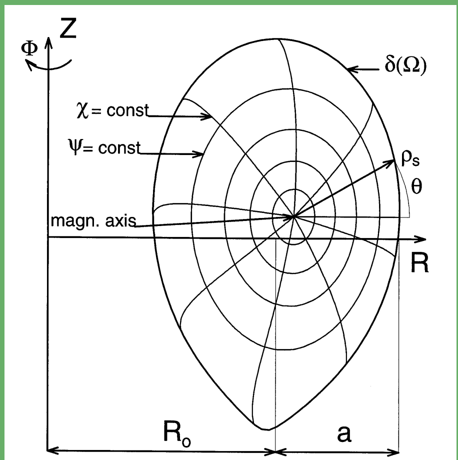
Energetic particle activities

• WP10-ITM-IMP5-ACT5: HYMAGYC

The new Frascati hybrid MHD-Gyrokinetic code, HYMAGYC:

- Thermal (core) plasma:
  - described by full, resistive MHD linear equations
  - e.m. potentials required by Gyrokinetic module: **A**, ϕ
  - Fluid nonlinearities will not be retained
- Energetic-ion population:
  - particle gyrocenter-coordinates are evolved by solving gyrokinetic eqs. up to order $O(\varepsilon^2)$ and $O(\varepsilon\varepsilon_B)$
  - perturbed quantities satisfy the nonlinear gyrokinetic ordering of Frieman-Chen, Phys. Fluids (1982) 23, 502
    $\omega/\Omega_E \approx k_{||}\rho_E = O(\varepsilon)$, $k_\perp\rho_E = O(1)$
    (with Ω_E the Larmor frequency and $k_{||}$ the component of the wave vector parallel to the magnetic field)
  - returns energetic particles pressure tensor Π^{ij} computed in terms of the particle distribution function in gyrocenter coordinates
- Flux coordinates system (s, χ, φ)

HYMAGYC



Energetic particle activities

• WP10-ITM-IMP5-ACT5: HYMAGYC

$t = 0$

Equilibrium (CHEASE)
- equilibrium solver
- mapping (modified version)

Equilibrium Interface Module
- compute Christoffel symbols
- scalar fields related to equilibrium quantities

Time loop $t_n = t_{n-1} + \Delta t$

MARST
- MHD module (evolutive version of MARS)
- Perturbed fields are advanced in time:
  MHD fields, $\phi^{(m,n)}(s)$, $A_\chi^{(m,n)}(s)$, $A_\varphi^{(m,n)}(s)$
- The divergence of the energetic pressure tensor terms added to the fluid momentum equation

MHD-GK Interface
- gauge transforms ϕ , A_χ , A_φ
- Fourier anti-transforms MHD fields:
  $\phi^{(m,n)}(s), \ldots \Rightarrow \phi^{(n)}(s, \chi), \ldots$
- compute derivatives of fields ∂_s, ∂_χ, $\partial_s\partial_\chi$

- Fourier transforms pressure tensor:
  $(\nabla\cdot\Pi)^{(m,n)}(s), \ldots \Leftarrow (\nabla\cdot\Pi)^{(n)}(s, \chi), \ldots$

Gyrokinetic module
- at $t = 0$: initialize simulation particles
- $\forall t$:
  - computes scalar fields with pert. quantities
  - pushes particles
  - computes $(\nabla\cdot\Pi)^{(n)}(s, \chi), \ldots$

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Energetic particle activities

- WP10-ITM-IMP5-ACT5: HYMAGYC
  - parallelization with a OpenMP (inter-node) + MPI (intra-node) scheme
  - run as standalone program on the Gateway
  - MHD module fully integrated with equilibrium CPOs (thanks to IMP12 collaboration) *see later for details*
  - Fast particles module currently under testing
  - integration with fast particles CPOs to be done

Energetic particle activities

- Inputs for MARST module from equilibrium CPOs (in order to substitute the standard input prepared by CHEASE)
  - Quantities required by MARS/MARST module:
    - integer and half-integer flux variable mesh: $s \equiv \sqrt{\frac{|\psi - \psi_0|}{|\psi_{\rm edge} - \psi_0|}} \in [0, 1]$
    - Fourier components of the covariant metric tensor elements; CPOs contain the contravariant elements (thus, the matrix needs to be inverted):

$$
\begin{aligned}
g^{ss} &= \left(\frac{\partial s}{\partial \psi}\right)^2 g^{\psi\psi} = \left(\frac{\partial s}{\partial \psi}\right)^2 |\nabla \psi|^2 \\
g^{s\chi} &= g^{\chi s} \left(\frac{\partial s}{\partial \psi}\right) g^{\psi\chi} = \left(\frac{\partial s}{\partial \psi}\right) \nabla\psi \cdot \nabla\chi \\
g^{\chi\chi} &= |\nabla \chi|^2 \\
g^{\phi\phi} &= |\nabla \phi|^2 \equiv \frac{1}{R^2}
\end{aligned}
$$

    - χ poloidal like angular variable, such that Jacobian is: $J_s = [(\nabla s \times \nabla \chi) \cdot \nabla \phi]^{-1}$
    - Equilibrium magnetic field, current, pressure: $B^\chi, B^\phi, j^\chi, j^\phi, p, dp/ds$
    - A vacuum mesh (simple model for free boundary modes)

Energetic particle activities

- Issues arisen during equilibrium CPOs interface (1)
  - 1D profile quantities `equilibrium%profiles_1d%...` (e.g., `%q, %psi, %F_dia, %ffprime, %p, %pprime`): data are "almost equispaced" in the variable $s \propto \sqrt{\psi}$
  - Coordinate system 2D quantities:

equilibrium%coord_sys%	**physical quantity**	**comment**
grid%dim1	ψ	"almost equispaced" in *s*, in principle different from 1D definition
grid%dim2	χ	χ mesh $\chi = (ndim2 - 1)/ndim2 * 2\pi$
grid_type	description	*Straight field line*: the only choice for HELENA, which implies also $J = \frac{qR^2}{2\pi F_{\rm dia}}$ *Non-straight field line*: choice available for CHEASE, $J_\psi = C(\psi) R^{\rm NER} \lvert\nabla\psi\rvert^{\rm NEGP}$
position%r position%z	$R(\psi, \chi)$ $Z(\psi, \chi)$	coordinates in the poloidal cross section
jacobian	$J(\psi, \chi)$	Jacobian
g_11, g_22, g_33, g_12	$g^{ss}(\psi, \chi)$, $g^{\chi\chi}(\psi, \chi)$, $g^{\varphi\varphi}(\psi, \chi)$, $g^{s\chi}(\psi, \chi)$	contravariant(!) metric tensor elements

Energetic particle activities

- Issues arisen during equilibrium CPOs interface (2)
  - Regular mesh don not means “equidistant mesh”!
  - signs for I_p and B_0 must be taken into account (note that usual MHD stability codes ignore those signs, whereas CPOs do not!)
  - Only one mesh is provided in the CPOs (the integer one, which includes the magnetic axis and the plasma boundary), thus interpolation is required: note that some of the metric quantities could diverge toward the origin, care should be taken in interpolating such quantities!
  - Also, interpolation of 1D quantities on the `dim1` mesh is required, in order to compute all the quantities required by MARS/MARST
  - Several issues on the Jacobian definition, choice of the coordinate system for the stability mesh, etc. have been considered and agreed between ITM (see WEB page https://www.efda-itm.eu/~wwwimp3/TEST/ITM/html/itm_conventions.html)
  - Not jet available in equilibrium CPOs:
    - maps $\psi(R, Z)$, $\chi(R, Z)$ (ready from IMP12?)
    - Christoffel symbols (require derivatives of the metric tensor elements)

Energetic particle activities

- Gateway MARS/MARST version
  - The exercise of modifying the MARS/MARST MHD module used by HYMAGYC in order to read the equilibrium quantities from the CPOs is almost completed
  - a C preprocessor produces the FORTRAN for standard use or the one required to interface the code with the CPOs:
    - transforms the module from a "`main`" to a "`subroutine(equilibrium_in)`"
    - declares `type_equilibrium`, and `interface` quantities
    - the standard input routine is substituted by the ones which reads the CPOs and computes all the derived quantities (`subroutine input_gw (equilibrium_in)`, which, on turn, call the module `read_eq_CPOs_MARS.f90`)
  - A driver to run and test the Gateway version of the code reading an equilibrium CPOs (`driver_mars_fftw_gw_linux.f90`) has been written
  - Tested on CPOs produce by HELENA and CHEASE
  - Still to be done:
    - write the XML code specific parameters inputs
    - write the ouput results to the MHD stability CPOs