EFDA Task Force
EUROPEAN FUSION DEVELOPMENT AGREEMENT
INTEGRATED TOKAMAK MODELLING

Fast Particles activities during WP10

IMP5 Project

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Physics motivation –

1. "The aim of the Integrated Modelling Project #5 on "Heating, Current Drive and Fast Particles" is to develop a package of codes prediction and interpretation of heating, current drive and fast particle effects. The areas to be covered include ECRH, ICRH, NBI, LH, alpha particles and fast particle interaction with instabilities. The ultimate goal is to enable self-consistent simulation of heating and current drive in the presence of fast particle instabilities, especially for ITER." (from *WP10-ITM-IMP5 Call for Participations*)
2. In a burning plasma, fast (alpha) particles are expected to transfer their energy via Coulomb collisions to the thermal plasma, thus providing a (nuclear self-) heating mechanism and a route to ignition. The fusion reactions and/or auxiliary heating systems generate energetic particles characterized by velocities in the super-Alfvénic range, and it is well known that they can resonate with, and possibly destabilize, shear Alfvén modes. The mutual nonlinear interaction of shear Alfvén and energetic particles can, in turn, affect the energetic ion transport and confinement properties.

Activity streamlines –

0. Porting of codes to the Gateway (WP10-ITM-IMP5-ACT1)
1. Benchmarking of linear MHD codes to assess Alfvén Eigenmode (AE) and Energetic Particle Mode (EPM) stability thresholds (WP10-ITM-IMP5-ACT3)
2. Code development for global stability analyses of Alfvén Eigenmode (AE) and Energetic Particle Mode (EPM) in realistic geometries and in the presence of non-perturbative fast ion excitations (WP10-ITM-IMP5-ACT5)

1. WP10-ITM-IMP5-ACT3

Two linear codes are being ported to the GATEWAY in order to participate to the benchmarking exercise to assess Alfvén Eigenmode (AE) and Energetic Particle Mode (EPM) stability thresholds (WP10-ITM-IMP5-ACT3): the **LEMan** code and the **LIGKA** code.

•**LEMan** (P. Popovich, W.A. Cooper, L. Villard, *Comput. Phys. Comm. 175, 250 (2006)*) is a full-wave code that has been designed to compute the propagation of waves in the Alfvén and Ion Cyclotron frequency ranges using a warm-plasma formulation for the dielectric tensor (N. Mellet *et al., Theory of Fusion Plasmas: Joint Varenna-Lausanne Int. Workshop, p. 382 (2006)*). It can deal with 3D geometries

•**LIGKA** is a linear gyrokinetic code for the description of background kinetic and fast particle effects on the MHD stability in tokamaks (Lauber et al 2007 *J. Comput. Phys. 226/1 447–65*). Recently, the NAG components of the eigenvalue solver for LIGKA has been replaced by SCALAPACK. This replacement is a non-trivial step since the solving algorithm for a problem depending in a non-linear way on the eigenvalue is quite complex, especially for the parallel implementation.

Deliverables before end 2010:

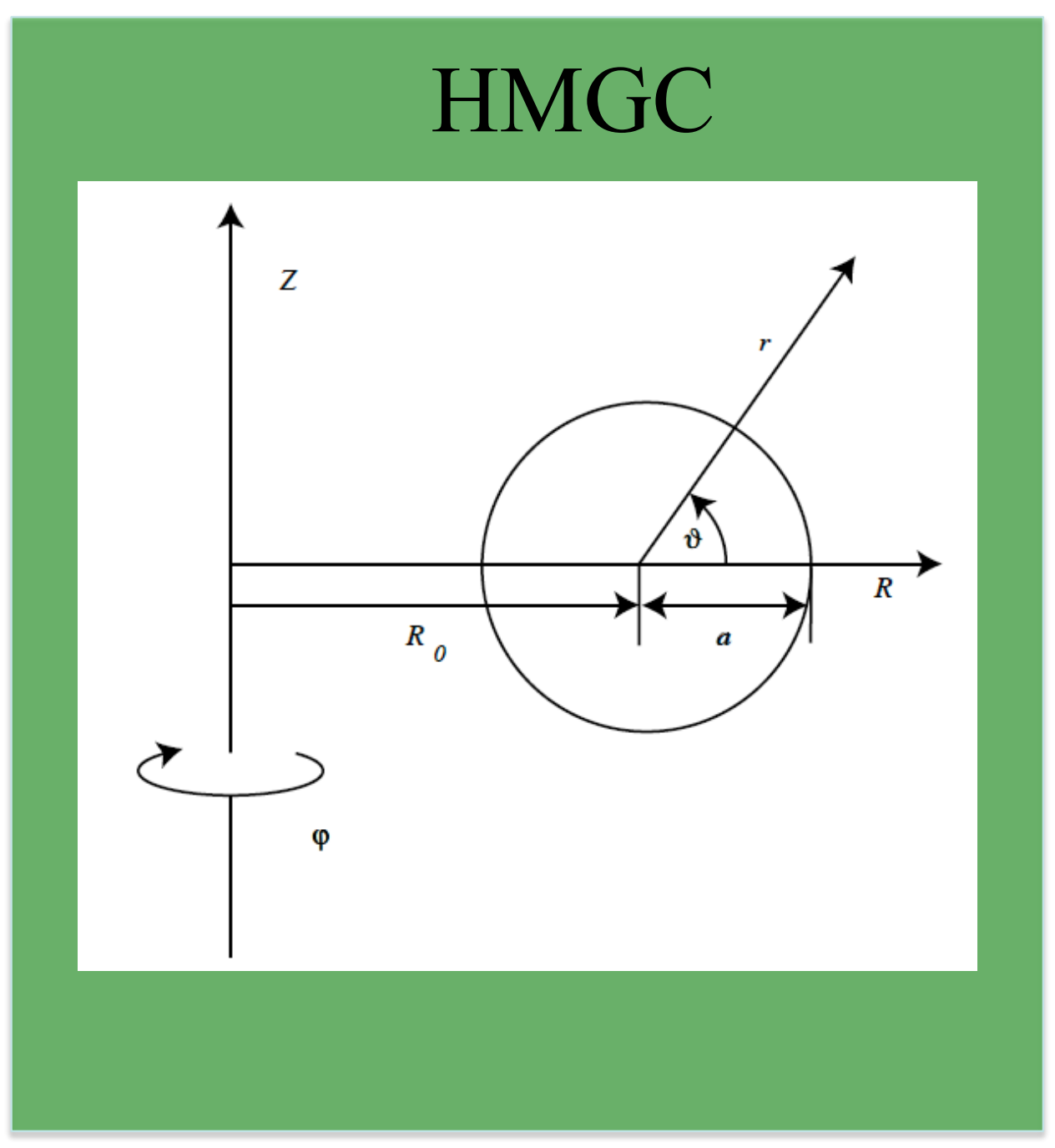
•It has been decided that some of the equilibria that are being used for the benchmark exercise under the ITPA Energetic Particle Physics Topical Group will be made available on the GATEWAY (thanks to ITPA)

2. WP10-ITM-IMP5-ACT5

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

- Thermal (core) plasma:
  - described by reduced $O(\varepsilon_0^3)$ visco-resistive MHD equations in the limit of zero pressure ($\varepsilon_0 \equiv a/R_0$ being the inverse aspect ratio of the torus; this model allows to investigate equilibria with shifted circular magnetic surfaces only).
  - MHD fields: ψ (poloidal flux function), ϕ (e.s. potential)
- Energetic-ion population:
  - described by the nonlinear gyrokinetic Vlasov equation, expanded up to order $O(\varepsilon)$ and $O(\varepsilon_B)$ with $\varepsilon \sim \rho_E/L_n$ (gyrokinetic ordering parameter, ρ_E being the energetic ion Larmor radius and L_n the equilibrium density scale length) and $\varepsilon_B \sim \rho_E/L_B < \varepsilon$ (L_B being the equilibrium magnetic field scale length), and in the $k_\perp \rho_E \ll 1$ limit (with $k_\perp$ the component of the wave vector perpendicular to the magnetic field)
  - energetic particle pressure: $\Pi_\perp$, $\Pi_\parallel$,
  - magnetic drift orbit widths fully retained,
  - solved by particle-in-cell (PIC) techniques.
- Coordinates system (r, θ, φ)

HMGC



Status and recent developments of HMGC with respect to ITM:

•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

Particle pushing

•Gyrokinetic eqs. of motion (only representative terms retained in this box):

$$\mathrm{d}\mathbf{R}/\mathrm{d}t = U\mathbf{b} + (q_E/m_E\Omega_E)\mathbf{b}\times\nabla\Phi_{\mathrm{eff}} + (\mu/m_E)\mathbf{b}\times\nabla\ln B \;\ldots$$
$$\mathrm{d}\mu/\mathrm{d}t = 0$$
$$\mathrm{d}U/\mathrm{d}t = -(q_E/m_E)\mathbf{b}\cdot\nabla\Phi_{\mathrm{eff}} - (\mu\Omega_E/m_E)\mathbf{b}\cdot\nabla\ln B + \ldots$$

•The *effective* potential is in the form:

$$\begin{aligned}\Phi_{\mathrm{eff}} = \; & \langle\phi(\mathbf{R}+\boldsymbol{\rho})\rangle - (U/c)\langle\delta A_\parallel(\mathbf{R}+\boldsymbol{\rho})\rangle + \ldots && O(\varepsilon)\ldots +\\ & - (U/\Omega_E)^2(\mathbf{b}\cdot\nabla)\mathbf{b}\cdot\nabla\langle\phi(\mathbf{R}+\boldsymbol{\rho})\rangle + \ldots && O(\varepsilon\varepsilon_B)\ldots +\\ & + (q_E/cm_E\Omega_E)\langle\mathbf{b}\cdot\delta\mathbf{A}(\mathbf{R}+\boldsymbol{\rho})\times\nabla\phi(\mathbf{R}+\boldsymbol{\rho})\rangle + && O(\varepsilon^2)\end{aligned}$$

with <…> being the average over the gyrophase θ

Both equilibrium and perturbed scalar quantities must be computed:

$$\mathbf{b}\times\nabla\Phi_{\mathrm{eff}} = \mathbf{e}_2(\mathbf{e}_1\cdot\nabla\Phi_{\mathrm{eff}}) - \mathbf{e}_1(\mathbf{e}_2\cdot\nabla\Phi_{\mathrm{eff}})$$

$$\begin{aligned}\mathbf{e}_1\cdot\nabla\Phi_{\mathrm{eff}} = \; & \langle\mathbf{e}_1(\mathbf{R}+\boldsymbol{\rho})\cdot\nabla\phi(\mathbf{R}+\boldsymbol{\rho})\rangle +\\ & + (2\mu/m_E\Omega_E)^{1/2}\underbrace{(\mathbf{e}_2\cdot\nabla\mathbf{e}_1\cdot\mathbf{e}_2)}_{\textit{equilibrium scalar}}\overbrace{\langle\sin\theta\,\mathbf{e}_2\cdot\nabla\phi(\mathbf{R}+\boldsymbol{\rho})\rangle}^{\textit{perturbed scalar}} +\\ & + \ldots\end{aligned}$$

Status and recent developments of HYMAGYC with respect to ITM:

•The code has been ported to the Gateway as a stand-alone module

•HYMAGYC has been parallelized with OpenMP (inter-node)+MPI (intra-node) parallelization scheme

•Equilibrium inputs to the MHD module (originally provided by CHEASE) has been substituted by equilibrium CPOs written by high resolution codes (e.g., HELENA and CHEASE): this has required a long and fruitful interaction with IMP12 during 2010 in order to debug and test the high resolution equilibrium outputs written in the equilibrium CPOs

Deliverables for the near future:

•Full interface with equilibrium CPOs (also for the Gyrokinetic part, e.g., Christoffel symbols, etc.)

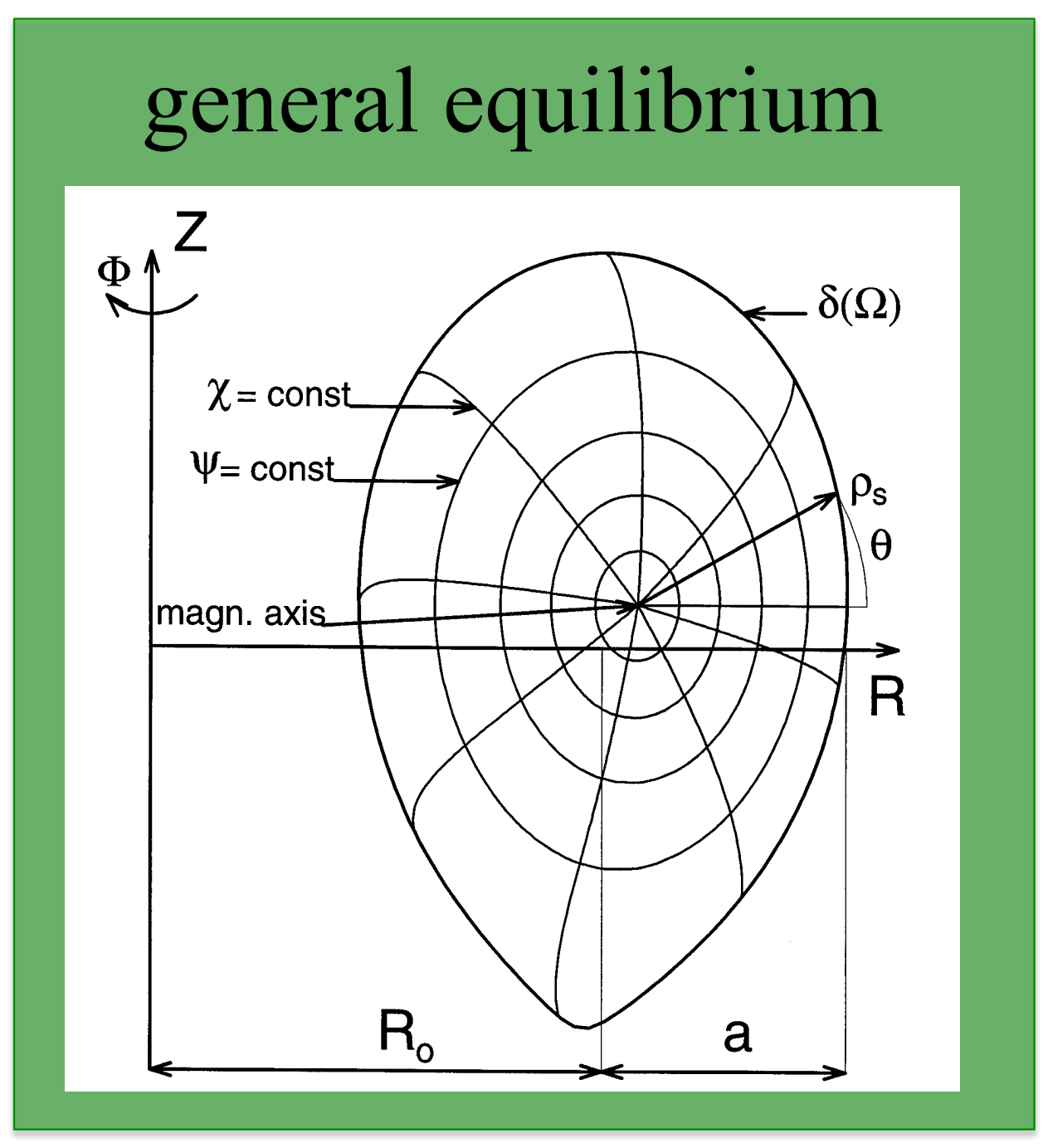
•Interface with energetic particle CPOs (e.g., equilibrium distribution function, ...)

•Proceed in testing phase

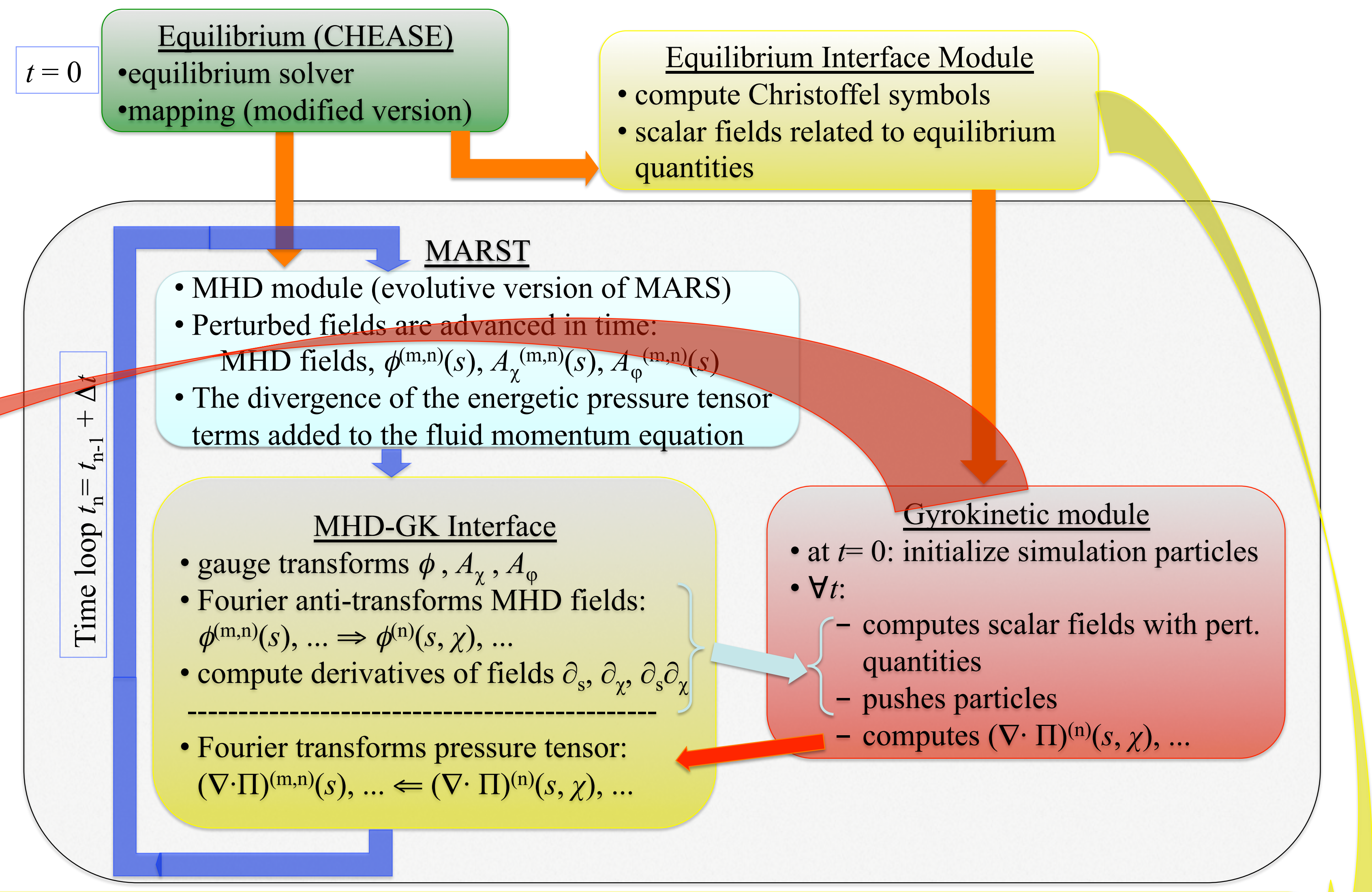
... to the new Frascati hybrid MHD-Gyrokinetic code, HYMAGYC:

- 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 $\omega/\Omega_E \approx k_\parallel\rho_E = O(\varepsilon)$, $\quad k_\perp\rho_E = O(1)$ (with Ω_E the Larmor frequency and $k_\parallel$ 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)

general equilibrium



Block diagram for the HYMAGYC code



$t = 0$

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

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

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

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

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 $(\nabla\cdot\Pi)^{(n)}(s, \chi)$, ...

Equilibrium Interface Module

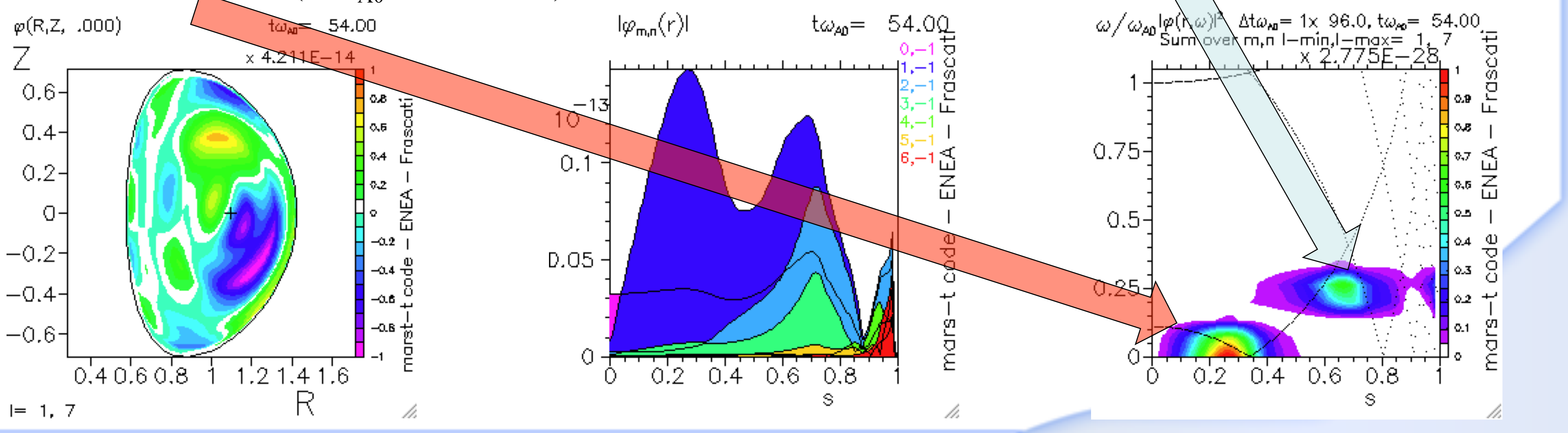
- Prepares:
  - $R(s, \chi)$, $Z(s, \chi)$, $\partial_s R$, $\partial_\chi R$, $\partial_s Z$, $\partial_\chi Z$, $s(R, Z)$, $\chi(R, Z)$, $g_{ij}(s, \chi)$ (metric tensor), $J(s, \chi)$ (Jacobian)
  - the contravariant components of: (1) equilibrium field $\mathbf{b}_{eq} \equiv \mathbf{B}_{eq}/|B_{eq}|$; (2) perpendicular versors $\mathbf{e}_1 = (\mathbf{b}_{eq}\cdot\nabla)\mathbf{b}_{eq}/|(\mathbf{b}_{eq}\cdot\nabla)\mathbf{b}_{eq}|$, $\mathbf{e}_2 = \mathbf{b}_{eq}\times\mathbf{e}_1$
  - the Christoffel symbols in order to compute the covariant derivatives of vector and tensor fields in a non-euclidean space: $\Gamma^i_{kl} = 0.5\,\Sigma_m g^{im}(\partial_l g_{mk} + \partial_k g_{ml} - \partial_m g_{kl})$. Note that these quantities are not available in the present version of the equilibrium CPOs.
- Regularizes quantities which diverge toward the magnetic axis, e.g.:

$$\Gamma^\chi_{ss} = 0.5[g^{\chi s}\partial_s g_{ss} + g^{\chi\chi}(2\partial_s g_{\chi s} - \partial_\chi g_{ss}) + 2g^{\chi\varphi}\partial_s g_{\varphi s})] \sim s^{-1}$$
$$s\Gamma^\chi_{ss} = 0.5[(sg^{\chi s})\partial_s g_{ss} + (s^2 g^{\chi\chi})s^{-1}(2\partial_s g_{\chi s} - \partial_\chi g_{ss}) + 2(sg^{\chi s})\partial_s g_{\varphi s})] \sim \mathit{const}$$

- Computes the scalar fields defined on the gyrokinetic grid and which contain only equilibrium quantities (computed at $t = 0$)

A JET equilibrium test case, n=1: two modes are observed,

- an Alfvénic mode (localized in frequency below the toroidal gap, $\omega/\omega_{A0} \approx 0.25$ and radially at $s \propto \sqrt{\psi} \approx 0.7$),
- and an internal kink ($\omega/\omega_{A0} \approx 0$, $s \approx 0.25$).



ITM General Meeting, 2010, Lisbon