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The Magnetic Fusion Simulation programme in CEA

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1- Introduction

New international flag for thermonuclear magnetic fusion energy research, the ITER project was approved and sited in Cadarache, France, by June 28th, 2005. Seven partners, Europe, Japan, Russia, China, USA, South Korea and India, representing more than half of the world population, participate into the project, which now enters its construction phase. The first ITER plasmas are expected by the end of 2016. ITER has a tokamak configuration, where the magnetic confinement of the plasma is ensured by superconducting toroidal and poloidal magnets, allowing long pulse operation (>400s). The nominal main parameters are major radius R=6.2m, minor radius a=2m, plasma current Ip=15MA, toroidal magnetic field on axis B=5.3T, elongation ε=1.85, triangularity δ=0.85. The maximum fusion amplification gain Q is expected to reach 10, the fusion power to reach 400MW and the nominal plasma duration to reach 400s. So-called ‘advanced regimes’ are also designed to maintain Q=5 on much longer time duration, prefiguring a reactor-like behaviour.

ITER is a major technological challenge, integrating many concepts developed in the past years on fusion experiments around large superconducting magnet systems, large volume vacuum chambers, high heat flux exhaust handling and vessel cooling (plasma facing components), particle flux management (pumping and fuelling), high incoming power heat fluxes (heating and current drive systems), within a nuclear environment. The question of plasma control is obviously addressed in order to run such plasma discharges at the relevant performance and safety level. But ITER is also a formidable scientific challenge, concentrating within 800m^3 of plasma all the complexity of fully ionized, magnetized, burning plasma physics, combined with plasma-wall interaction issues. This represents a challenging integration issue, both experimentally and at the modelling level. The fusion theory and modelling community is constantly improving the physics understanding of such plasmas, involving various coupled phenomena, often non-linearly.

The EURATOM-CEA Association participates actively to this world-wide theory and modelling effort along several lines of actions:

- First principle modelling, dedicated to the understanding of fundamental phenomena,
- Ad-hoc modelling, developing simplified models, parameterized and adjusted both on experimental observations and first principle results.
- Real-time modelling, developing « ultra fast » modules for device control & operation (not developed in the present paper)
- Modelling technologies, as a necessary support to operating sophisticated coupled descriptions within a reliable and high-quality environment.

The paper illustrates this commitment to the development of a next generation source of energy.

2- First Principle Theory and Modelling

a. Gyrokinetic modelling

Amongst the key issues to be addressed, the nature of heat transport in tokamak plasmas occupies a very specific place. It has been understood rather rapidly that the heat (and particle) transport in tokamak plasmas had significant turbulent components, making it significantly larger than expected by the so-called neo-classical theory. This theory simply assumes that the charged particle follow the orbits deduced from the confinement magnetic field configuration, and experience collisions. In fact, several turbulence mechanisms superimposes this neo-classical background transport, and degrades the resulting energy confinement. It is of utmost importance to understand and correctly model the plasma turbulence for the existing and future devices. Several approaches exist to the modelling of turbulence. One can assume that the plasma is constituted by (a) magnetized fluid(s) or be more ambitious and consider the time evolution of the distribution functions of the various species. This a priori forces to solve the time-dependent 6D Vlasov equation (for each species), self-consistently coupled to the electro-neutrality equation that couples the turbulence fields to the plasma. Fortunately in this approach, one can decouple the very fast gyro-motion of particles across magnetic field from the slower guiding centre motion, and then reduce the space dimensionality by one. In this 5D “gyrokinetic” frame, the plasma turbulence can thus be fully modelled, in particular within realistic tokamak geometry. The counterpart is obviously the extremely large computer capability request. This can be understood when examining the space and time scales involved in such a problem. Let us simply consider the ion turbulence. The relevant space scale for such a turbulence is the so-called normalised Larmor radius ρ^* (i.e. the characteristic ion Larmor radius normalised to the minor radius of the device). In present and coming devices, ρ^* is of the order 10^{-3}. This means that at least 3 orders of magnitude must be considered in space to model the full range between the characteristic plasma section. The characteristic ion turbulence time scale τ^* is of the order of 10^{-5} s, when the energy confinement time in present and coming devices is of the order of 1s, again meaning that at least 5 orders of magnitude have to be covered by the simulation. The gyrokinetic approach, when covering this 5D approach in present and coming devices, then requires the use of the cutting edge world range computers. This is not mentioning the electron turbulence that would require 3-4 orders of magnitude more in terms of computer capability and is still largely out of reach.

The GYSELA code, presently developed at CEA, is a 5D gyrokinetic model that describes the time evolution of the full ion distribution function of ions (so-called “full-f”) in a tokamak environment [Y. Sarazin et al., Plasma Phys. Control. Fusion 47 (2005) 1817–1839]. The plasma geometry is discretized along the minor radius (r), poloidal (θ) and toroidal (φ) angles, when the kinetics is discretized along the guiding centre velocity along the confinement magnetic field ($v_{//}$) and the magnetic momentum μ. The 64 Teraflops TERA10 computer is presently used for simulating plasma turbulence down to ρ^*-values of the order of 2.5-5 10^{-3}. As an example, figure 1 shows one of the non-linear validation cases of GYSELA, when simulating the so-called “Cyclone” case [Dimits et al., Phys. Plasmas **7** (2000) 969]. Figure 1 shows the simulation trajectory of the normalized transport coefficient versus the normalized temperature gradient, in both cases when Zonal flows are simulated or not. One clearly sees that zonal flows, nowadays observed in fusion devices, play a significant role in the turbulence evolution.

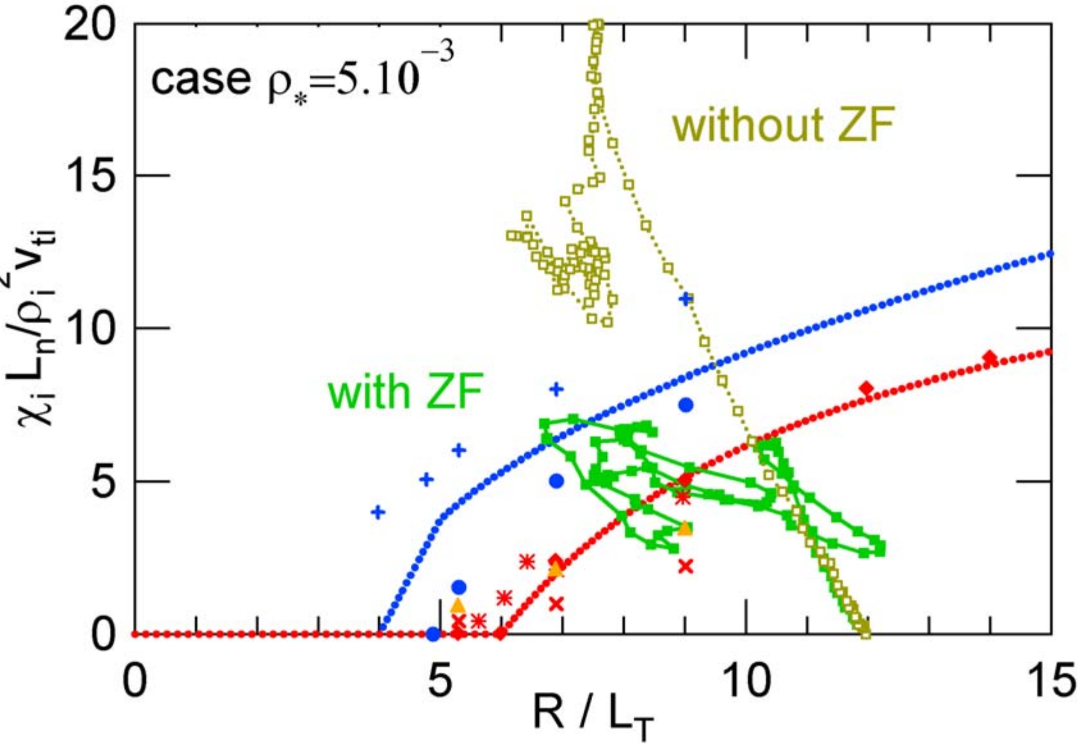

Figure 1: GYSELA 5D simulation of the Cyclone case, both with and without Zonal Flow (ZF) simulation.

The simulation displayed in Figure 1 was performed at $\rho^*=5\ 10^{-3}$, on a 5D grid ($\rho\times\theta\times\varphi\times v_{//}\times\mu$ = 256x256x64x32x8) of $2\mathrm{x}10^9$ points, representing 4500 mono-CPU hours on TERA10 (64 processors were used in that case).

b. MHD modelling

The specific difficulties of MHD simulations are the wide range of timescales (from Alfvén time (10^{-6} - 10^{-7} s) to equilibrium time scale (~1s)), the near singular mode structures (low magnetic Reynolds number ($S \sim 10^6 - 10^{10}$)), and the fact that the exact magnetic geometry plays an important role (the structure of magnetic surfaces, presence of X-point(s) and metallic walls must be taken into account). The JOREK code is a reduced MHD model in toroidal geometry, evolving poloidal flux, vorticity, density and temperature. It uses a finite element discretization in poloidal plane: Fourier or finite elements in toroidal direction, finite elements aligned on equilibrium flux surfaces It includes X-point and open field lines, mesh refinement in 2D, and a variable number of harmonics. It is parallelized using MPI. The large sparse system of equation is solved using parallel direct sparse matrix libraries and requires large memory capability.

The code is presently exploited for simulating the Edge Localized Mode (ELMs) activity in tokamaks. This edge MHD activity occurs when the plasma develops an edge transport barrier, which translates into the existence of a large pressure pedestal in the vicinity of the last closed flux surface. This strong pressure pedestal might be driven unstable and generate fast relaxations called ELMs. The exact mechanisms for ELM triggering and relaxation is under intense investigation [Huysmans G., Plasma Phys. Control. Fusion 47 (2005) B165–B178], as they potentially drain a significant fraction of the energy stored in the plasma and redistribute it to the plasma facing components, possibly causing damages. A code like JOREK is used both for phenomenology and optimisation in such cases. Figure 2 shows an example of the evolution of the so-called ballooning mode (toroidal number n=6), where edge density filaments are observed and sheared off by large n=0/m=0 induced poloidal flow (m is the poloidal mode number).

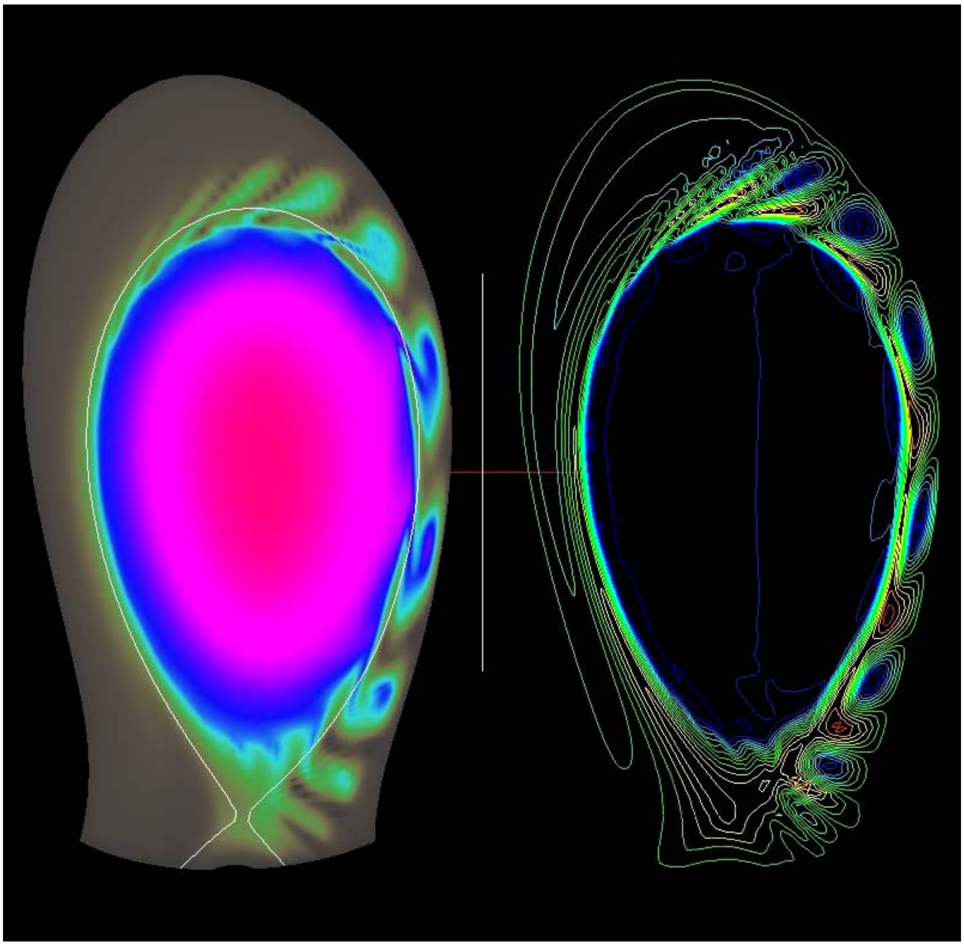

Figure 2: JOREK output. Density (left) and flow (right) of a n=6 ballooning mode

The code is also being used to investigate the influence of external magnetic perturbations on such modes, in charge of preventing the pedestal pressure to reach the levels where ELMs are triggered. Such kind of ELM pacing techniques are already used on several existing fusion devices (DIII-D, MAST, ...) and are under investigation for ITER.

c. Wave-Particle Interaction for Heating and Current Drive purposes

Application of externally launched multi-megawatt waves in tokamak devices is one of the ways used to both heat the plasma and help it reach the ignition conditions, and/or drive non inductively the plasma current and help the configuration to reach steady-state. Several ranges of frequency and resonant damping mechanisms are used for such kinds of purposes, from the ion cyclotron range of frequency (ICRF, several tens of MHz) to the electron cyclotron range of frequency (ECRF, 100-200 GHz).

The first example of modelling is taken in the ICRF through the development of the EVE code, based on the full hamiltonian description of the interaction between the waves present in the plasma and the ion and electron species. In fact, a compressional magnetosonic wave is coupled to the plasma through a resonant loop antenna located at the periphery of the device (some centimetres outside the last closed flux surface). The wave propagates radially into the plasma and experiences damping (possibly ion cyclotron or parallel Landau + transit time magnetic pumping on electrons). Part of the energy flux can also experience mode conversion into ion Bernstein or ion cyclotron waves and be further damped by ions or electrons. These very complex propagation-absorption schemes require a sophisticated modelling level and a full wave description. The physics features of EVE are the wave equations solved in terms of potentials (vector and scalar) trough a variational formulation, the particle orbits written in action-angle coordinates together with a Finite Larmor Radius expansion. The numerical features are a parallel code, finite elements (cubic + quadratic), Fourier expansion in poloidal and toroidal angles, Fortran 90 (for the core), and Python (for post-processing). An example of wave-field phenomenology is shown on figure 3, for an ASDEX-U Deuterium plasma, minority Hydrogen heating scheme, F=33.5MHz, n=20)

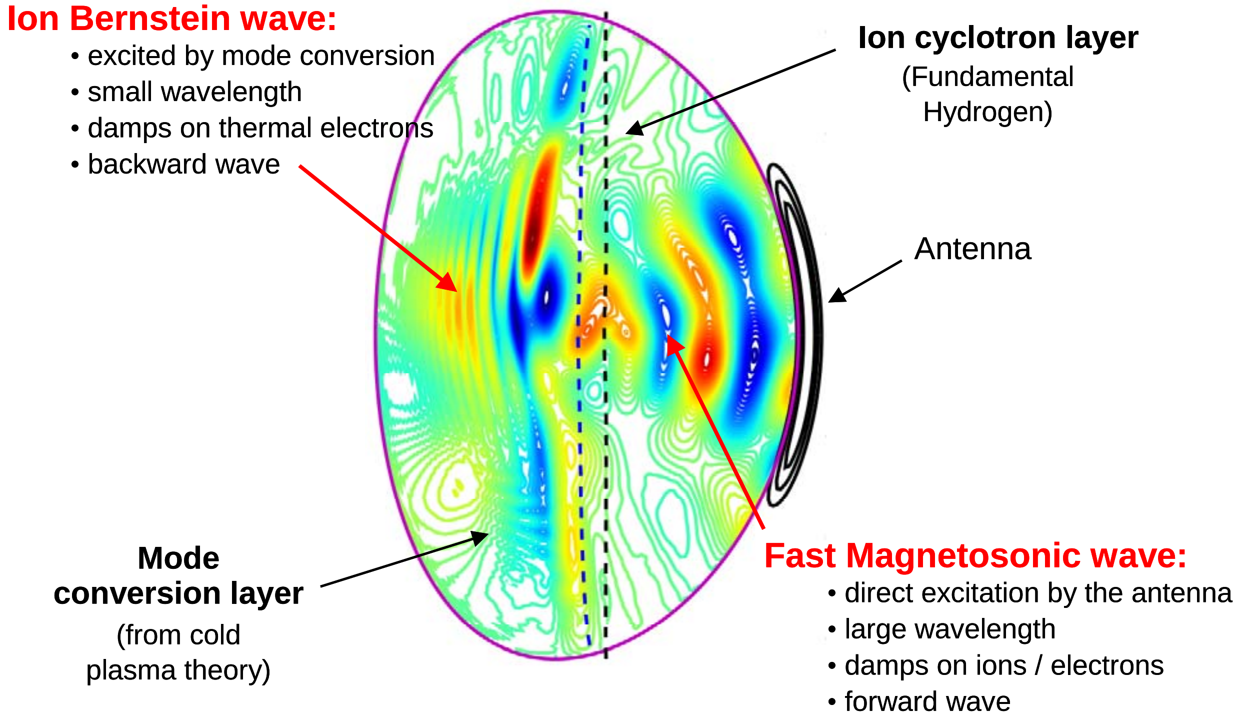

Figure 3: EVE simulation: left-handed electric field

The second example of modelling is taken in the field of wave-electron dynamics, at higher frequencies, i.e. when the ray-tracing wave propagation assumption is valid. C3PO, a universal ray-tracing code, has been developed with arbitrary dielectric tensor (cold, warm, hot, relativistic) and arbitrary tokamak magnetic equilibrium. This allows us to propagate in any tokamak geometry Lower Hybrid waves (used for current drive purposes), Electron Cyclotron as well as Electron Bernstein waves, and of course light. Along the ray, the wave damping is then assured by the resolution of the drift kinetic equation. A 3-D relativistic bounce-averaged drift kinetic solver (LUKE) has been written for this purpose. It operates in the thin banana limit (suitable for electron dynamics), with arbitrary tokamak magnetic equilibrium, and contains the anomalous fast electron radial transport consistent with the quasilinear theory. The time scheme is fully implicit or reverse, with incomplete LU matrix factorization, and parallel processing, making it extremely fast. The C3PO+LUKE simulation was recently applied to assess the operating frequency of the Lower Hybrid Current Drive (LHCD) system of ITER. Figure 4 shows the propagation of the rays, the deformation of the electron distribution function in the directions parallel (//) and perpendicular ($\perp$) to the confinement magnetic field, as well as the power and current density deposition profiles, in different situations of parallel index of the injected wave. This calculation shows the expected off-axis deposition that will help an ITER discharge entering in the so-called “advanced mode of operation”.

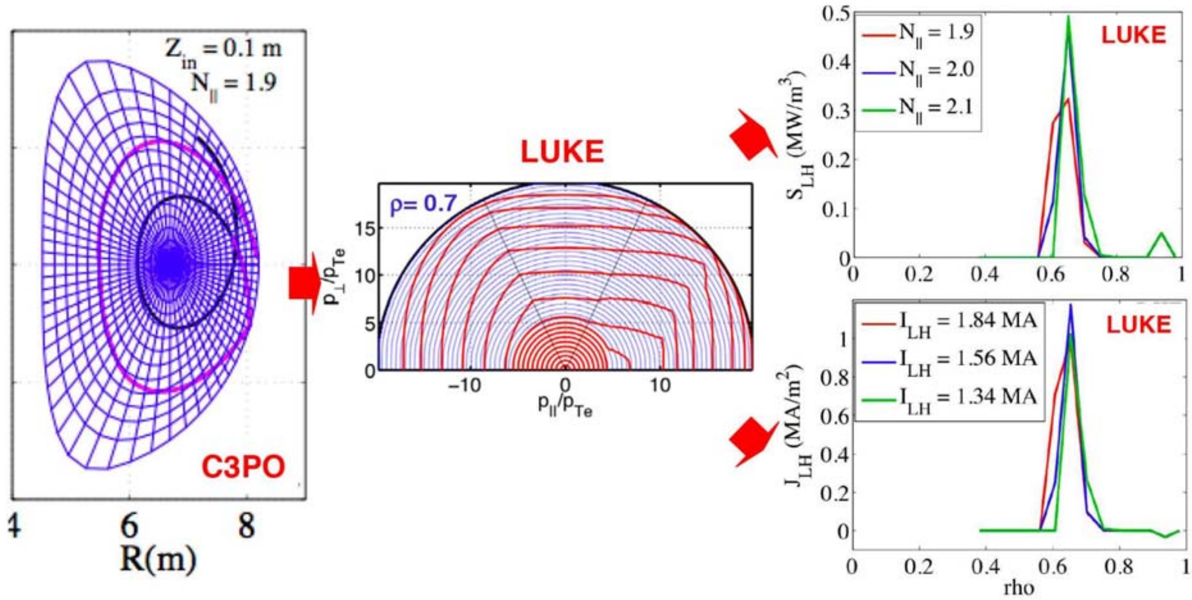

Figure 4: C3PO+LUKE simulation of LHCD in ITER (5GHz, Advanced scenario IV, P_{LH}=30MW)

3- The CRONOS integrated modelling package

The ultimate goal of magnetic fusion modelling is the deliverance of the so-called plasma scenarios, i.e. of the full time sequence of the plasma response (temperature, density, …) to the prescribed parameters (magnetic field, plasma current, heating and current drive excitations, …). Therefore modelling naturally splits into two categories: the numerical descriptions directly derived from first principles (as seen above), and the ad-hoc models, deduced either from them or from experiment, more suitable for fast simulations. A fully first principle description of all phenomena, though desirable, cannot be envisaged in the near future for both reasons that some of the descriptions still do not exist and a scenario computed this way would require a computer capability totally out of reach at present. It is thus interesting to carefully discriminate between the physics processes and adjust the level of the descriptions to the physics phenomena.

A tokamak discharge is first of all a transient inductive discharge from the primary of a transformer into its secondary, namely the plasma annulus. The backbone equation to solve is thus a multi-diffusion equation, giving the time evolution of the radial profiles of the temperatures (one per species), the densities (one per species), the plasma current density and the various components of the plasma rotation (fig2). The geometry is intrinsic, i.e. to be computed self consistently with the plasma state, and ruled by the so-called Grad-Shafranov equation. In the core of a tokamak plasma, the toroidal axisymmetry allows the reduction to a 2-D problem and leads to a 1-D flux coordinate system, but in other magnetic configurations (stellarator, …) and/or in the region where the plasma directly interacts with the plasma-facing components (the ‘edge’) the geometry must be computed in 3-D. It is important to note that the various diffusion equations are a priori coupled, and unless experimental profiles can complement, they must be solved together. Finally, the 1-D (or 2-D) diffusion equations can be solved exactly, provided the geometry is given. The Grad-Shafranov equation requires extra constraints that either come from experiment providing information on pressure and/or current profiles, or from the self-consistent computation of the pressure and current profiles.

The second issue to be addressed is the determination of the various transport coefficients that appear in the diffusion equations (diagonal and cross terms). A large part of the first principle physics presently under active development and discussed in §2a is located here. The transport coefficients reflect for a large part the complexity of the problem, revealing the strong non-linearities and coupling phenomena that rule the plasma evolution. Even when assuming that the plasma transport (heat, particle, momentum, current) is diffusive and local (which might be disputed), it is certainly impossible to ignore its turbulent nature, often involving simultaneously several turbulence sources together with the so-called neo-classical background, as naturally deduced from the effect of collisions on the confined particle trajectories. There exists a very large set of codes and descriptions for transport coefficients. This goes from ad-hoc analytical expressions, mostly deduced from experimental fits, to their derivation from first principle turbulence computation. The direct derivation from first principles being not available yet, several codes propose intermediate approaches, estimating the most unstable turbulent processes and proposing semi ad-hoc transport coefficients.

The following step concerns the determination of the source and sink terms which enter the diffusion equations. The first item deals with the plasma particle fuelling, achieved through gas puffing at the edge or high speed (~1km/s) ice pellet injections. Problems of gas penetration in the edge plasma configuration or pellet ablation in hot dense plasmas are of concern. Reversely, a steady-state plasma requires a constant skimming and pumping to insure the fuel renewal, and this deserves detailed modelling to optimize the configurations. Similarly, the injected power, both used to heat the plasma and bring it to ignition or to drive non-inductively part of the plasma current in order to prolong the plasma duration, must be modelled. The power can be transferred based on two different physics schemes

- the resonant absorption of wave power: Modelling such effects require to solve the complete set of Mawxell + Vlasov equations on a priori non Maxwellian distribution functions, using the relevant geometry for the wave propagation, and in the presence of collisions. Examples were given in §2c.
- the injection of suprathermal atoms (i.e. atoms more energetic than the background plasma ions): this is achieved by generating in a cold plasma ion source either positive or negative ions, then accelerate them to ~ 100kV for positive ions and up to 1MV for negative ions. These fast ions are then neutralised in a gas chamber and then injected into the tokamak plasma. Through collisional drag and scattering they thus transfer their energy. The modelling aspects are now rather well mastered and routinely used, involving extremely detailed Monte Carlo simulations basically.

On the top of such terms, one must also take into account the intrinsic sources of power and particle. The most important is obviously the alpha-particle production generated by the D-T reactions, but the various components of the power radiation (impurities, bremsstrahlung, synchrotron,…) are also mandatory to account for the detailed power balance. At this level, it is important to note that models might require information on individual particle trajectories as some configurations may not fully confine such high energetic ions.

The power must also be extracted as it reaches the plasma facing components. The plasma-wall interaction physics provides further modelling complications as it involves i) non axisymmetrical configuration and ii) non fully ionized plasmas. A very detailed edge plasma description is crucial to correctly connect the hot core plasma to its material environment and estimate its mutual influence with the plasma facing components (impurity production, material erosion and redeposition, hot spots, radiofrequency wave coupling characteristics, …).

Finally, an integrated modelling must be able to check the overall stability of the plasma discharge, subject to magnetohydrodynamics (MHD) instabilities either limiting the performance or even disrupting the magnetic configuration (see §2b). This both occurs at the plasma core (periodic relaxations of the pressure profile, creation of magnetic islands, …) or at the plasma edge (periodic relaxation of the pressure profile towards the plasma facing components, ..). Most of the relevant MHD modelling must include non-ideal (i.e. resistive) effects and include non-linear saturation of modes, within the exact geometry, in the presence of supra-thermal particles as well. Such computations are amongst the most CPU time demanding as well.

The CRONOS suite of code, under long term development at CEA, addresses this chain of coupled descriptions models and codes [Basiuk V. et al., Nucl. Fusion 43 (2003) 822-830]. Figure 5 gives a schematic idea of the complexity of CRONOS.

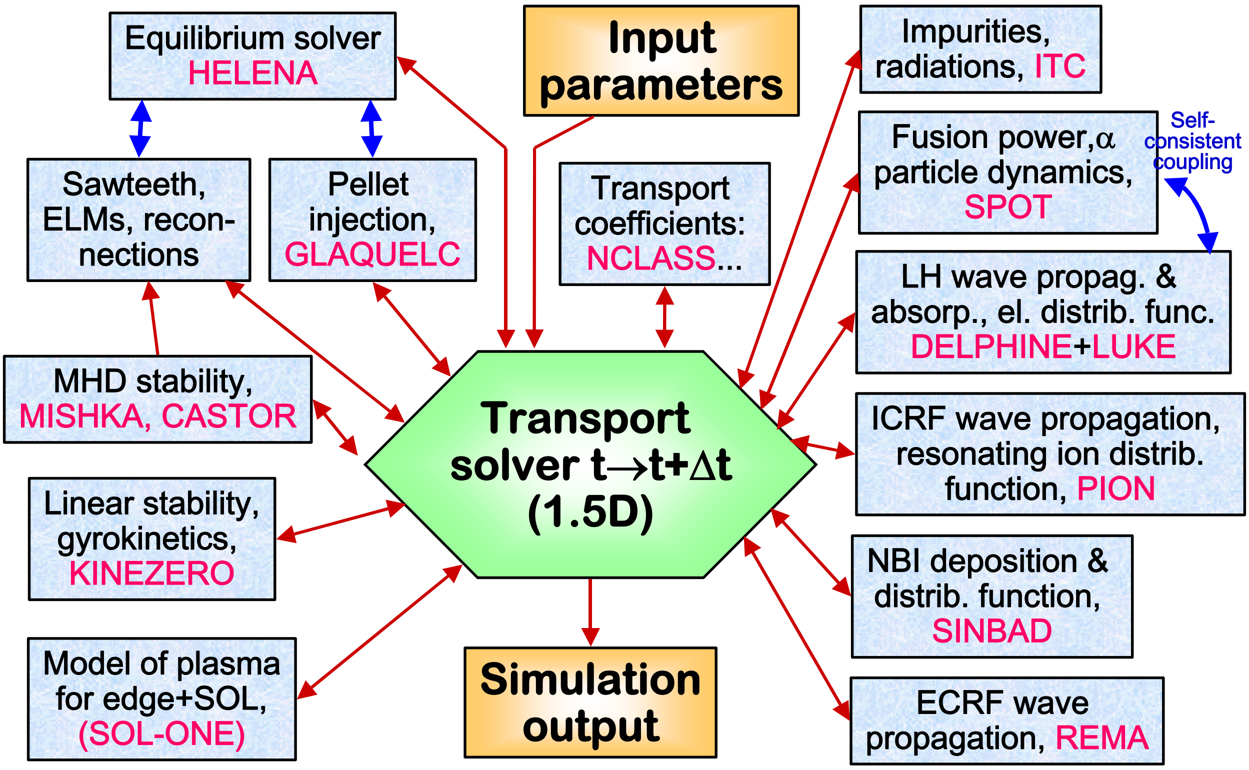

Figure 5: the CRONOS suite of codes (present version #4)

CRONOS does not fulfil yet the ultimate goal of a complete fusion device simulator, but participates actively to this long term and world-wide effort. Its purpose is both to interpret existing experiments, and to predict the experiments to come. As an example, Figure 6 gives details on the reconstruction of an advanced tokamak JET discharge [Litaudon X et al, Nucl. Fusion 44 (2002)]. CRONOS is in this case able to reconstruct in details the various components of the plasma density current, in terms of inductive and non inductive (LHCD, Neutral beam current drive, bootstrap current), in such a way that the time evolution of the measured internal inductance (Li), the loop voltage (Vloop), the Faraday rotation angles and the Motional Stark Effect angles are perfectly reproduced during all the discharge duration.

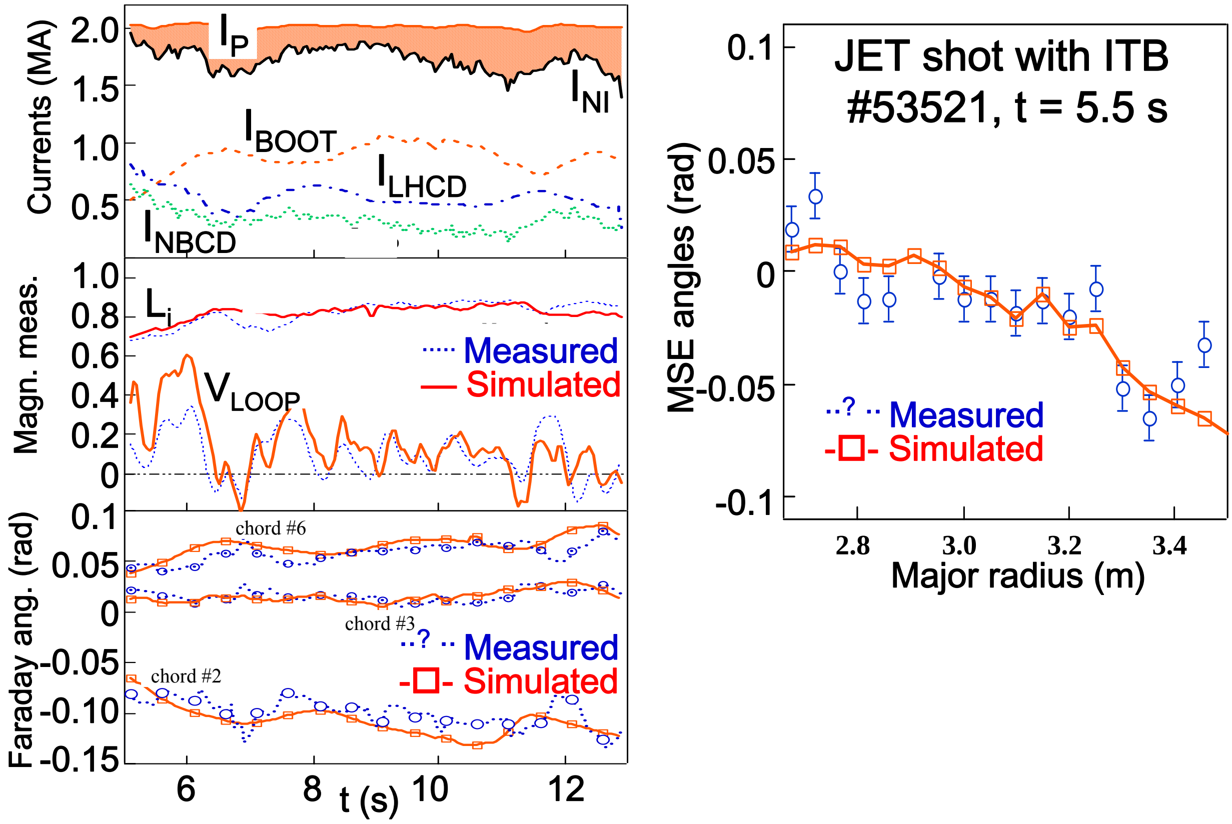

Figure 6: CRONOS interpretative simulation of JET discharge #53521

Such kind of detailed reconstruction is extremely helpful in both understanding the interplay between the phenomena and optimizing them in terms of plasma performance and stationarity. CRONOS to that respect can easily be used from interpretative to partly or fully predictive mode.

Another important aspect brought by CRONOS, in relation with experiments on actual devices, is its built-in feature allowing the test of any kind of feedback algorithm. This is of particular importance for operating large tokamak devices in the so-called advanced modes of operation, close to the MHD limits.

4- Participation into the European Task Force on Integrated Tokamak Modelling and the Modelling technologies

Obviously all the modelling activity described above is closely linked to the European Task Force on Integrated Tokamak Modelling (EU-ITM-TF) that coordinates the development of the European Modelling tools, in particular for ITER, together with the similar initiatives amongst the ITER partners. But on the top of this first principle and integrated modelling tasks, CEA also participates actively into the definitions of all the so-called “modelling technologies”. For this purpose, the EU-ITM-TF is running the Infrastructure & Software Integration Project (ISIP), in charge of developing the following series of dedicated tools:

- A universal data structure, based on XML schemas describing all the data objects that are manipulated by modellers
- A universal data and database access, transparent to users.
- Database exploration tools

- Platform(s) for manipulating automatically and chaining codes and modules (encapsulation)
- Software et middleware (for computer grid access)
- Visualisation tools

In 2007, Europe will also start operating a unique entry point (The European Fusion Gateway) to its integrated modelling tools, namely a front server enabling secure connection to all services through user profile management, a code repository, a data repository, the universal (data) access layer, the Code Platform server, the necessary high-speed connection links and the necessary access to the fusion computers (grid) and databases.
These tools intend to allow the large modelling community to share data, codes and modules, in a quasi-transparent way and a user-friendly environment. ISIP specifications also comply with the necessary QA requirements set (or to be set) by customers like ITER, including traceability, archiving, documentation, ...

5- Conclusion

Magnetic Fusion research generates a very broad and challenging activity in terms of modelling and simulations: first principle, ad-hoc and integrated modelling, real time simulation. The magnetic fusion simulation programme at CEA covers many aspects, in particular turbulence, MHD, RF physics as far as first principle theory is concerned. It develops and runs a performant interpretative and predictive simulator, and addresses issues related to real time and feedback algorithms.
The CEA simulation programme participates actively into the European task force on Integrated Tokamak Modelling, which is structured for providing in term to fusion devices the complete set of integrated tokamak simulation tools (first principle, ad-hoc models and technologies). This very long term activity is ambitious and leaves space for collaborative actions.

6- Credits

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