

European Transport Solver: first results, validation and benchmark

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I) Introduction

The European Integrated Tokamak Modelling Task Force (ITM-TF) is developing a new type of fully modular and flexible integrated tokamak simulator. This simulator allows assembling elementary physics modules together, combining them graphically into complex and flexible physics workflows. The “workflow” is the suite of calculations carried out during a simulation. One among the applications of the simulator is to build the European Transport Solver (ETS^[3]), an Integrated Transport solving similar equations to ASTRA^[1], JETTO^[2] and CRONOS^[4]. Though the capability of the simulator goes well beyond this application, designing graphically the physics workflow for solving integrated core transport equations is both a challenge and an occasion to demonstrate the possibilities of the simulator.

This paper presents first results of the prototype ETS workflow under the ITM-TF framework. This framework uses the Kepler software for designing and executing physics workflows. The ETS workflow includes a time loop evolution and a convergence loop inside, solving core transport equations for the poloidal flux and electron energy. Equilibrium and transport coefficients (anomalous and neoclassical) are calculated consistently with the evolution of the core plasma profiles. The results of the ETS are benchmarked against CRONOS simulations for an experimental discharge from the Tore Supra tokamak. The comparison is made at the level of each module, i.e. neoclassical module, equilibrium and transport solver. A good agreement between the ETS results, CRONOS results and experimental data (flux consumption for the moment) is found, which validates this ETS workflow implementation

II) KEPLER^[5], actors and workflow

KEPLER was chosen by the ITM-TF to design various physical workflows addressing the tokamak modelling. Its intuitive graphical interface, associated to various libraries (control structure, loop, graphics ...), allows to link actors by lines which represent both the workflow and the dataflow. An ITM-TF actor under Kepler is a modular physics component that solves a given type of physics problem, e.g. equilibrium reconstruction or solving the transport equation. The ITM-TF has developed novel concepts for data interfaces between physics modules: the Consistent Physical Objects (CPO)^[6]. These objects are hierarchical structures containing all data referring to a physical problem (e.g. an equilibrium, a source term, a set of core plasma profiles, information on MHD linear stability) or to a tokamak subsystem (e.g. a diagnostic or a heating system). In the ITM-TF workflows, actors communicate information on the physical state of the plasma and the tokamak subsystems through the CPOs.

The workflow presented (fig. 1) solves the current diffusion equation along time. Two different solvers have been used in this workflow, one of them being based on the CRONOS solver (and called #1 hereafter), the other (#2) being described in [1]. Only ohmic cases are treated, using an NCLASS^[7] actor for neoclassical resistivity and bootstrap current, and various equilibrium actors (HELENA21^[8], HELENA^[8], CHEASE^[9]). This variety of choices illustrates modularity of the system. In this workflow, the typical CPOs exchanged are: equilibrium CPO filled by equilibrium solvers; “coreprof” CPO (set of core plasma profiles)

produced by the transport equation solver, “neoclassic” CPO gathering the information from the neoclassical code NCLASS.

The ETS workflow shown here corresponds exactly to the algorithm used in the CRONOS Integrated Modelling code^[4], which has been translated graphically into the KEPLER environment. The time loop and the solver convergence loop are now explicitly described as a part of the KEPLER workflow, instead of being hidden in a library. The simulation shown in figures 2 and 3 correspond to the experimental Tore Supra discharge 34796 (magnetic field $B_0=2.24$ T, plasma current $I_p = 750$ kA, line averaged density $n_l=210^{19}$ m⁻²).

As KEPLER inside the ITM is still in its development phase, we should have validation tools. Thus a similar FORTRAN workflow was constructed on the same platform. This tool combines to a direct comparison with a cronos run through MatLab function is a key point for the verification of the workflow. It will also allow determining the CPU cost of using KEPLER instead of a FORTRAN workflow.

The transport solver actor, core of the workflow, receives from other actors all the information’s it needs through the following CPO: equilibrium, profile, transport and source. It computes the matrix coefficients of the current diffusion equation, solves the diffusion equations with their boundary conditions and computes few outputs such as the new total current profile (q profile, and integrated quantities, self inductance ...). Internal parameters of the solver (time step, number of equation) are set as actor or workflow parameters. The CPO “equilibrium” may have a different radial grid than “coreprof”. An actor makes the resampling of the equilibrium on the radial grid of the solver, filling a new occurrence of the CPO equilibrium (see [3] for the concept of CPO occurrences).

Each CPO has its own time base. The workflow time base is constructed during the execution depending on the internal time step of the solver. Events such as pellets or MHD events are easily added inside KEPLER. It is just an actor which is inserted in the workflow and modifies a given CPO type. For instance, the sawteeth event (which has its own CPO) will have as input the kinetic profiles (“coreprof”) and the equilibrium (“equilibrium”) and as output (depending on a sawteeth crash) new kinetic profiles and new poloidal flux (ψ). The equilibrium should be recomputed taking into account these new values. An actor is then introducing to compute from the poloidal flux (ψ) the new current density profile.

III) Benchmark and results

The Benchmark exercise of the workflow is made in two parts. First of all each separate modules (equilibrium, neoclassical) are validated (comparison with the CRONOS version). To obtain this validation a shot of Tore Supra is used (shot #34796) where the only non inductive current is the bootstrap current. The dedicated CRONOS run for this shot is in good accordance with the experimental data which means that all the kinetic profiles (electron, ion temperature), the charge effective (density) are validated. On the fig. 2, the comparison of the bootstrap current is done at two times, one with the version of NCLASS inside the CRONOS Integrated Modelling Code, one with the version of NCLASS inside KEPLER. The agreement is reasonable.

In a second time a full run is made (only the current diffusion equation is used, the so-called “interpretative mode”) under Kepler and comparison of plasma parameters such as current profile (CRONOS, fig 2), or the q profile (CRONOS, fig 3) are undertaken as these quantities are two of the main results obtained by solving the poloidal flux diffusive equation. Good agreements are obtained on the two comparisons, the high percentage error (>20%) value observed at the edge concerns very low value of the current density (idem for the current bootstrap). The reconstruction of the self inductance gives an error around 1% compared to the CRONOS one and ~7 % compared to the experimental one (deduced from magnetic diagnostic).

Different workflows are available (two transport solvers, three equilibriums). The three equilibriums were tested in the same workflow with the same input data from 1.97 s to 2.06 s. The figure 4 shows a small discrepancy between equilibrium solvers at the centre of the plasma, where the reconstruction of the flux surfaces is the most difficult.

For the comparison of the two transport solvers, the same equilibrium (helena21) is kept. For the moment, the way to generate the current profile (J_{moy}) from the poloidal flux, using the following formula:

$$J_{moy} = \frac{\langle \vec{J} \cdot \nabla \phi \rangle}{\langle \frac{1}{R} \rangle} = \frac{\langle \frac{\vec{J}_\phi}{R} \rangle}{\langle \frac{1}{R} \rangle} = - \frac{\frac{\partial}{\partial \rho} \left[V' \frac{\partial \Psi}{\partial \rho} \left\langle \frac{|\vec{\nabla} \rho|^2}{R^2} \right\rangle \right]}{\mu V' \langle \frac{1}{R} \rangle}$$

needs a derivative function which is different for the two solvers (sol#1 and sol#2) as seen in figure 5 showing the current profile after 30 ms of diffusion for a Tore Supra shot (#34796) with a small edge discrepancy and a higher one at the centre (but concerning one point).

IV) Conclusions

For the first time, a core transport equation solver is explicitly coded as a graphical workflow. First results have shown a very good agreement between the ETS workflow under KEPLER and the CRONOS Integrated Modelling code^[2]. The modularity of the workflow has allowed comparing various equilibrium solvers and transport solvers without modifying the workflow structure (just replacing one actor by another, data management remains completely identical thanks to the CPO concept). This is just the beginning of this endeavour: the direct database access to experimental databases for retrieving input data is foreseen for the end of this year. For the moment, no optimisation has been done for the CPU time consumption. The construction of more complex workflow, including source code, transport coefficient and other diffusion equation is in progress (the FORTRAN version is written). Finally, the ITM-TF system under KEPLER has proved its capability to link actors developed by different persons inside a collaborative workflow.

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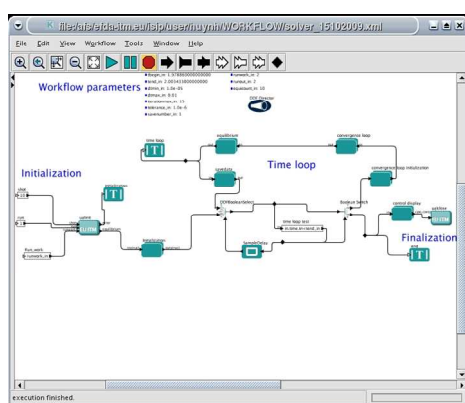


Figure 1: graphical workflow addressing the current diffusion equation. The full actors are composite actors

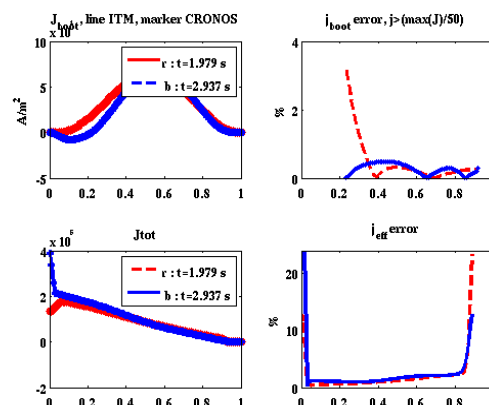


Figure 2: up : bootstrap current comparison and the error
down : total current density

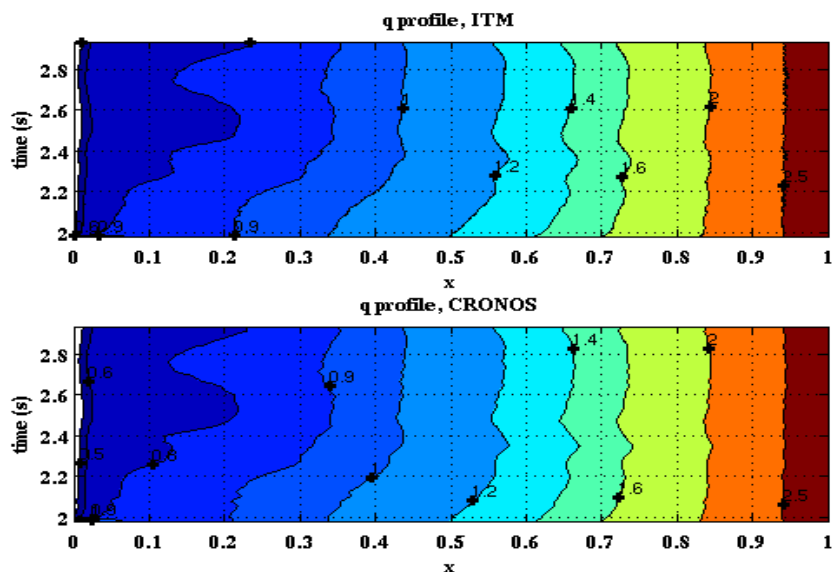


Figure 3: results of the simulation for an ohmic shot of Tore Supra (#34796). The top graph correspond to the ETS workflow under Kepler with solver #1 and equilibrium HELENA21, the bottom graph to the CRONOS Integrated Modelling Code ^[4].

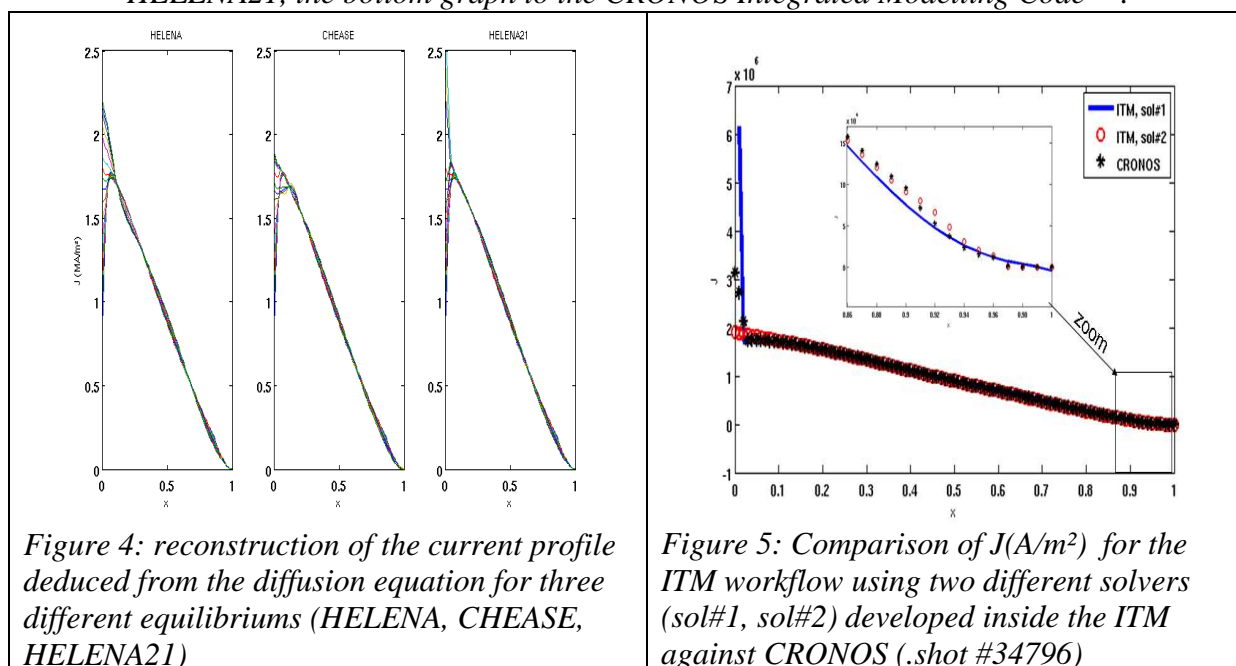


Figure 4: reconstruction of the current profile deduced from the diffusion equation for three different equilibriums (HELENA, CHEASE, HELENA21)

Figure 5: Comparison of $J(\text{A/m}^2)$ for the ITM workflow using two different solvers (sol#1, sol#2) developed inside the ITM against CRONOS (.shot #34796)

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