38th EPS Conference on Plasma Physics (2011) P1.105

Development of the DINA-CH Full Tokamak Simulator

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Introduction A wide variety of tokamak plasma simulator classes has been exploited, roughly grouped as: a) prescribed transport, prescribed boundary for the simplest cases, b) fixed or prescribed boundary transport simulators, c) free-boundary evolution with prescribed transport simulators and finally d) free-boundary with transport self-consistent with the boundary evolution. In the mid-1990's, at the time the basic ITER designs were being developed, transport modelling was less advanced than today and intriguingly, the most challenging class of self-consistent free boundary codes was the most popular. It was only later, with advanced understanding of transport that the present class of prescribed boundary transport codes developed into today's popular tools. In the context of the mid-1990's the candidate self-consistent simulation codes were restricted to TSC, the most advanced, DINA [1], relatively new and CORSICA, more primitive at the time with a restricted current diffusion model. The ITER expert group encouraged a benchmarking of these codes and a programme of model validation was launched on the TCV tokamak, as a continuation of a then existing validation programme of linear control modelling [2]. The choice of the code to be benchmarked fell upon the DINA code and this paper summarises the development phases.

Development Initial benchmarking took the existing linear modelling benchmarking experiments on TCV [2] and repeated them on the DINA code [3]. The benchmarking was considered a success but the work had to be carried out by the DINA team due to the complexity and mono-bloc nature of the DINA code. A second benchmarking exercise was then performed in the same environment to validate the dynamics of VDE's on which the vertical stabilisation control modelling depends intimately. The results [4] were very encouraging and demonstrated, in the specific conditions of the highly elongated TCV vacuum vessel, non-exponential growth as the location of the plasma current moved downwards towards the base plate, creating an S-shape VDE. This second benchmarking encouraged us to develop a new version of DINA in which the control modelling could be extracted from the equilibrium and transport solver. Matlab Simulink® was selected as the framework for this development.

At the time this choice was being made, it was decided to make two enhancements to the DINA code. Firstly, the ongoing ECRH and ECCD experiments on TCV required a heat deposition algorithm which aligned the beams in real space rather than in the radial plasma coordinate, such that displacement of the equilibrium naturally led to a change in the radial deposition profile. Secondly, the DINA intrinsic transport models were considered too restrictive and an option was generated to provide the DINA solver with the output of an external solver. This revision of the function of the monobloc DINA solver to function as a single one time-step solver within the overall control of a discrete time solver inside the Matlab Simulink® framework was named DINA-CH and delivered first results in 2002 [5].

DINA-CH evolved through a small number of versions, making enhancements, but the principal gain was twofold, stability of the solver and flexibility of the Simulink® user platform which could be developed in parallel by multiple users. The use of DINA-CH extended to MAST (for which some enhancements to the solver numerics were required) and to AUG (which required a modification to the circuit equations to include the Passive Stabiliser Loops) but effort was continually made to retain a single core version of the solver including these specific enhancements as switchable options. The externalising of the non-solver functions allowed, for example, development of synthetic diagnostics (bolometry, neutron camera and interferometer) using a single XML-driven module.

Work using DINA-CH was by then oriented towards ITER and the simple transport models used to date were considered inadequate and we searched for an enhanced transport solver, finally selecting CRONOS for its wide library and Matlab implementation. Conversion of the CRONOS solver to a single step transport module was performed with CEA and started delivering results with this expanded functionality in 2005 [6].

The ITER work led to convincing demonstrations of the complete hybrid scenario respecting the PF system design limits and including studies of the effect of LHCD obtaining the correct current profiles at the end of the current ramp-up [7].

Other applications The appropriate use of DINA-CH is best restricted to studies which cannot be carried out using prescribed boundary codes. Examples of such use cases already developed using DINA-CH are (i) handling VDE disruption forces, (ii) modulating the equilibrium to extract drift-less equilibrium quantities, (iii) modulating heat deposition and loop voltage to expose cross-modulation effects.

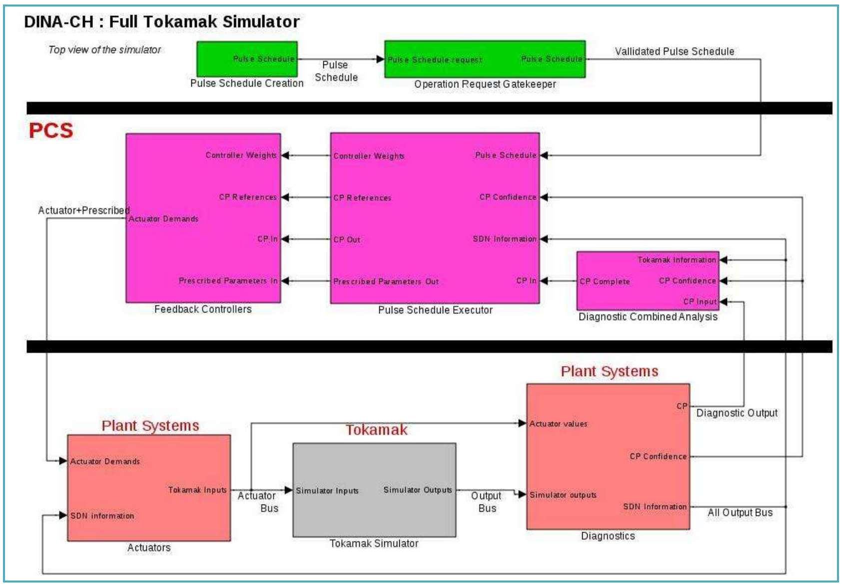

Figure 1 Current top view of the DINA-CH simulator, reflecting the current PCS architecture under development

Current status The developments in 2010 involved a restructuring of the overall Simulink® part of the simulator with two goals. Firstly, the top view was restructured (Figure 1) to represent the current ideas inside the development of the ITER PCS, specifically to reflect the on-the-fly modifications to the pulse schedule, and the creation of the pulse schedule itself; doing this helped identify some structuring elements discussed below. Secondly, the data required to perform a simulation have been reorganised to reflect a more realistic management of a simulation in the way experiments are handled. This current version is now being used to develop scenarios and to develop on-the-fly scenario optimisation [9].

Lessons learned The principal motivation was to benchmark a specific free-boundary solver and the success of this mission developed into the evolution of the full self-consistent tokamak simulator and its framework. The next generation of tokamak simulators under development for ITER will rely on a full appreciation of the good and bad things learned from past experience with simulators and we mention the most salient points.

Developing an architecture within a commercial framework has frequently been questioned, but this approach has borne fruit, releasing the code users from any development of the framework itself, and allowing the simulator to evolve without effort to absorb any new functionalities offered. The choice of a fixed step simulator within this framework is less clear since it merges two concerns, firstly the fixed step for numerical solution of the solver and secondly the fixed step required for discrete time control algorithms. This approach does not allow increasing the solution step size when in a relatively quiescent phase of the pulse, but it always respects the PCS step. At the same time, it avoids “fictitious” stepping of an implicit solver creating a false sense of success and noise free actuator signals. Reflecting a structuring of the control data in a data-driven sense has proven helpful. Respecting data-driven interfaces between PCS and the plant systems is natural and straightforward. The long ITER simulations led to the addition of an improved restart functionality which has proven to be essential. Interrupting the simulation is done by the framework.

A major weakness at present is the complexity of the interface between the specific solvers and the outer environment. The lack of imposed standards (this point was already taken on board by ITER) and a variety of dimensions and grids creates a problem of interfacing the 10's of data samples generated for each time-step and these have to be matched between the solver world and the real world of actuators and diagnostics. All codes would benefit in the long term from standardisation here, as is done in the EU ITM framework.

The complexity of the generated data is equal to or greater than an experiment, and would benefit from interfacing to the typical experiment analysis tools, although the use of Matlab for both experiment and modelling analysis helps.

Acknowledgements Fruitful interactions with the ITER PCS IPT are warmly acknowledged. The work was supported by the Fonds National Suisse de la Recherche Scientifique and partly funded with support from Fusion from Energy. It was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This publication reflects the views only of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

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