Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Development of a generic multipurpose tokamak plasma discharge flight simulator

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Tokamak
Flight simulator
Plasma control
Integrated tokamak modeling (ITM)

ABSTRACT

The operation of present day tokamak and future machine like ITER is more and more demanding in terms of plasma control both for increasing plasma performance, stability and ensuring machine protection. Additionally saving experimental time by validating the pre-programmed plasma scenario through a simulator is also of major importance. These issues highlight the necessity to build new tools such as a generic multipurpose plasma discharge flight simulator. Such a project has been recently started at CEA and is based on the integrated tokamak modeling task force formalism and simulation platform. The paper reports on the present status of the project, reviewing in particular the needs for new tool development, the architecture of the generic multipurpose tokamak plasma discharge flight simulator, with the different software/hardware interfaces. A first test case of this tool in the "full simulation" modes and using the European simulation platform is discussed.

1. Introduction

The optimization of present tokamak plasma experiments and the preparation of ITER operation highlight the needs of new plasma discharge simulation tools: the access to high performance relies more and more on advanced control schemes, such as MHD modes or plasma profiles control [1,2] that are to be designed by extensive simulations before experiment; the machine protection issues, that are becoming crucial with water-cooled and/or metallic wall devices, require a very careful off line and online check of the plasma discharge behavior. Experimental time and cost saving call for a more systematic and more extended pre-pulse validation of the plasma discharges settings and real-time data processing codes. These needs will definitely be essential for the operation of ITER.

Up to now several tools have been developed specifically for application on a dedicated tokamak [3–6] but none of them is able to fulfill in a single tool all the needs, especially to provide access to a wide range of physics/engineering models and to address at the same time the plasma performance and machine protection issues. This motivated the development of generic multipurpose tokamak plasma discharges flight simulator (GMFS) at CEA. It is generic in the sense that it makes use of the tokamak engineering and plasma physics data standardization defined under the European integrated tokamak modeling task force (ITM-TF) [7], and thus may be, in principle, applied to any tokamak facility. It is multipurpose in the sense that it allows both stand alone tokamak discharges simulation in a "full simulation" mode and also several "hardware in the loop" modes where a more or less extended part of the real tokamak plasma control system (PCS) is included. These last modes, which are of course partially depending on the PCS technology particular to a given facility, will be developed on Tore Supra, as a test case.

This paper is devoted to the description of the GMFS project, and reports on its present development status. Section 2 provides a detailed description of the needs in terms of tools for the development of new control algorithms, pre-pulse validation and post-pulse analysis. It results, in particular, in the functional specifications of the GMFS. Section 3 outlines the architecture of the GMFS describing the different modes of operations and discussing the technical choices. Section 4 presents a first test case in which a plasma shape controller based on the ITER geometry has been developed and validated using the "full simulation" mode of the GMFS.

2. GMFS functional specifications

The GMFS requirements are driven by the objectives of plasma discharge performance and safe tokamak operation. Pre-pulse checking which is actually not systematically made on the existing facilities will certainly be of major importance for ITER.

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To be able to reach high performance plasma discharges in steady state regime, a high degree of active control, not only of global parameters, but also of internal profiles is required. Plasma stability, particle and energy transport are all strongly dependent on the plasma internal profiles of current, pressure, toroidal rotation, etc., so that advanced control methods and new algorithms need to be developed. Most controllers on operating tokamaks have been developed using semi-empirical methods and are mainly based on simple PID. The new plasma control needs require the development of model-based feedback design approach. For that purpose, plasma control-oriented models have to be developed and advanced control algorithms have to be tested on simulation platforms. Moreover, the control needs are still evolving, for instance burn control is hopefully expected to become a very important issue within ITER operation. Thus a simulation platform able to integrate in a versatile way a wide range of physics models to build up a relevant simulation is of major importance to handle emerging issues and concepts. This calls also for the development of a comprehensive library of basic physics models, which is clearly lacking in the fusion community.

On the other side, the safe tokamak operation, including the real time handling of any unexpected events, is becoming recognized as a major issue, especially for facilities provided with actively cooled plasma facing component, metallic first walls and high internal plasma stored energy. It is already the case for Tore Supra, for JET with the new ITER like wall to come and definitively for ITER. Tokamaks require the orchestration of more than 50 systems including several sub-plants (cryogenic plant, magnetic coils, water cooling loops, multi megawatt heating systems, etc.), as well as plasma diagnostics. Thus, setting up a system allowing the management of abnormal situations to recover the plasma performance in safe conditions instead of terminating the plasma discharge is a key issue overtaking the scope of the present fusion devices especially to be able to reach long duration high performance plasma discharges. This domain is relatively new and is quickly growing up, in particular to cover the issues related to ITER operation. The development of new tools suitable to handle these issues requires to integrate to the physics models developed earlier, engineering models, which describes the behavior and limits of the subsystems.

One of the most demanding aspects of present and future tokamak control is the coupling between the different control fields (plasma equilibrium control, kinetic control, MHD control, machine protection, etc.), which are often handled independently in present experiments and the associated challenge of the actuators sharing. This clearly points out the need for integrated controls and overall discharge management schemes. This point highlights the need to build versatile simulation being able to account for these coupling.

In this way, the development of a new controller is a step by step process (Fig. 1), which has to consider the previously mentioned issues. A 1st step consisting in designing the control algorithms can be performed in a fully simulated mode to develop and improve the controller. It must embed physics and engineering models. The 2nd step aims at checking the implementation of the control algorithm in the tokamak PCS software/hardware. It is performed in a so called “hardware in the loop” mode where the plasma response is again provided by the physics/plant simulator while the control algorithms and diagnostic data processing are run on the physical PCS units. The final step is the validation on real plasma experiments.

The pre-pulse validation of parameter settings provides the first line of defence to identify any problem that may appear during the plasma discharge such as excess of currents requested to the poloidal field system or any gap to operating instructions, which could lead to a plasma termination. Such functionality is becoming important in particular for ITER where the time dedicated to the experimental sessions has to be optimized. This highlights the need to have a simulator which can be interfaced to the tokamak database and which is running fast enough to simulate the entire plasma discharge in a few minutes. So that it can validate, before running any plasma discharge, a set of pre-programmed parameters. An additional need consists in the capability to upload onto the tokamak database a set of simulation parameters to run a plasma discharge based on a simulation.

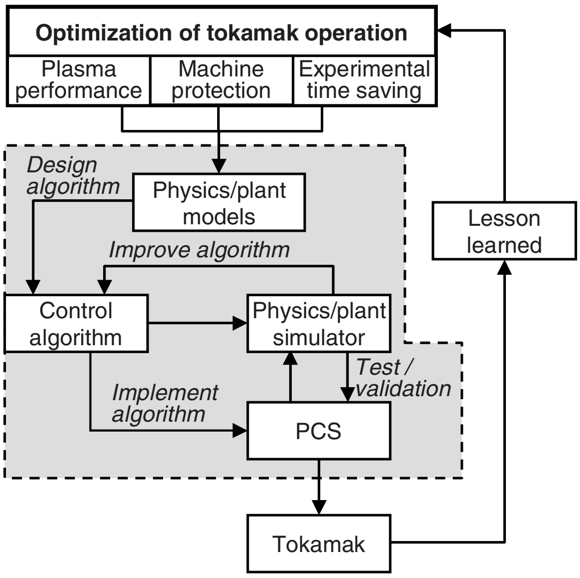

Fig. 1. Steps and iteration for the development of control algorithms.

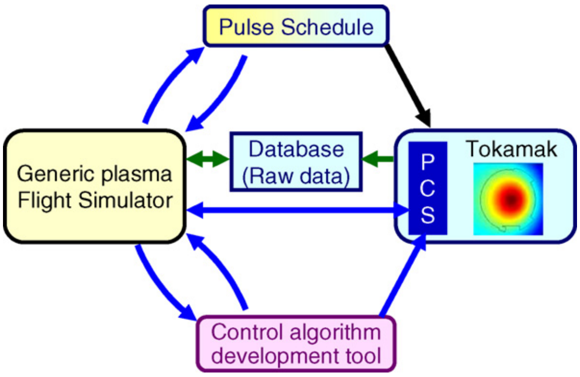

Fig. 2. Functional diagram of the generic multi purpose plasma flight simulator (blue items sketch the plant control systems including the plasma itself; green items account for the ITM-TF tools; the pink items account for the control toolbox software and the arrows account for the interfaces that must be developed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

3. Architecture of a generic multi purpose plasma flight simulator

Considering the whole set of requirements and to benefit from the large effort performed under the ITM-TF aiming at developing a modular and flexible integrated tokamak simulator, the decision has been taken to build the GMFS using the ITM-TF framework. Moreover, ITM-TF aims at providing a suite of validated models in support of the fusion program, targeting the preparation and analysis of future ITER discharges. These physics and engineering models will thus be available to the GMFS. Based on this strategic choice the functional specifications of a GMFS is derived and a functional diagram is proposed (Fig. 2). As far as the functional aspects are con-

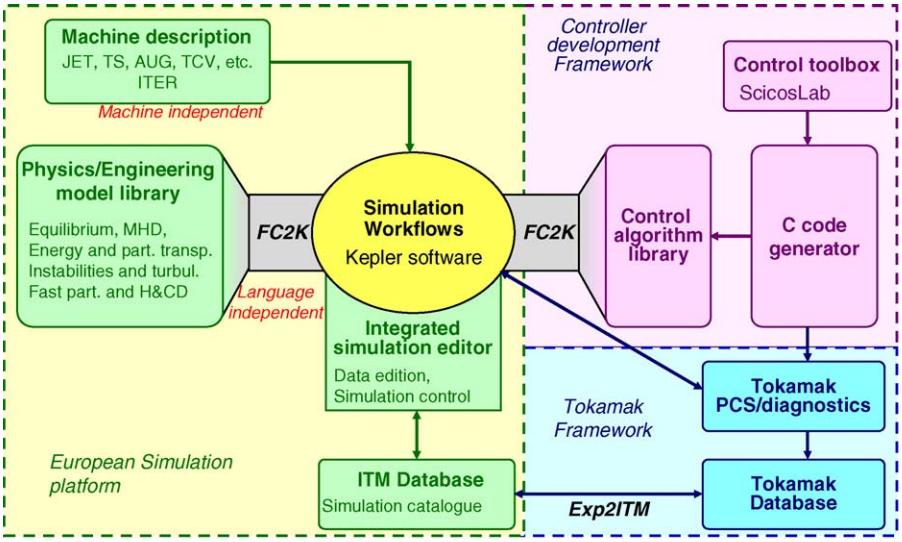

Fig. 3. Architecture of the generic multi purpose plasma flight simulator components.

cerned, there is a symmetry between the fully simulated operating mode and the real experimental plant:

- Browsing and setting up the simulation parameter is done by the integrated simulation editor (ISE), which is the equivalent of the tokamak pulse schedule editor.
- A control toolbox provides a friendly development framework to design and test the new control algorithms against control oriented simplified models beforehand. An automatic code generation is required to allow interfacing both to the ITM-TF simulation platform, where more sophisticated physics/engineering models can be found, and to the PCS units. At present the developments have been performed using the open source Scicoslab/Scicos tool [8]; a work is on going under ITM-TF to be able to use Matlab Simulink as well.
- The ITM-TF simulation platform is based on the Kepler open source software [9] allowing to design and to execute workflows.
- The switches shown on Fig. 2 are used to select the GMFS operation mode: the fully simulated" mode and the so called "hardware in the loop" mode and a wide range of mixed modes.

The architecture of the GMFS (Fig. 3) has been designed to facilitate the interfacing with the real plant and the ITM-TF simulation platform. The main idea is that the physics and engineering models are used as elementary blocks called "actors" in the Kepler software workflow. Kepler is based on modular workflows organized around elementary actors that can be linked together through user friendly graphical interfaces. Any physics or engineering model written as a C, C++ or fortran function can be wrapped by a semi-automated ITM-TF tool called fc2k (Fortran/C to Kepler) to become a Kepler actor. Using the C code generation capability of the control toolbox, and the fc2k tool, the controllers developed within the control toolbox can be converted into Kepler actors. The system to be controlled is then simulated by putting in a Kepler workflow a set of validated models provided by the ITM-TF and a set of controllers provided by the control algorithm library.

The dataflow between actors requires new concepts of data structure and workflow organization, which is handled by the definition of standardized physics-oriented input/output units, called consistent physical objects (CPOs) [10]. The CPOs contain physics data into standardized blocks becoming the natural transferable unit between actors of the workflow. The simulation parameters are set-up using the ISE and stored in the simulation database. A mapping of the local experimental tokamak databases onto the ITM-TF data structure (CPOs) implementation is ongoing. It will allow to build simulation from "real" data and conversely to use the reference defined in the simulation database to run a "real" experiments. It is worth to say that the C function generated through the control toolbox tool can be implemented in the tokamak PCS to be run on plasma experiments. A detailed technical description of the interfaces can be found in [11].

4. Application to a first test case

As a first application, we have decided to validate the GMFS interface between the control toolbox and the Kepler software considering the development of a control algorithm with the fully simulated mode. The example is based on the development of a feedback loop to control ITER plasma boundary through a set of 8 gaps. The control-oriented model is based on a standalone version of the free boundary equilibrium code CEDRES++ [12,13]. CEDRES++ has been used to derive a linear model around the reference equilibrium with $\delta\,\mathrm{Gap} = M_G\,\delta\,I_{PF}$ (where δGap is the gap distance, δI_{PF} is the current in the poloidal field coils and M_G is a 8 × 12 matrix) and to calculate the mutual inductance matrix L_{ij} of the system includ-

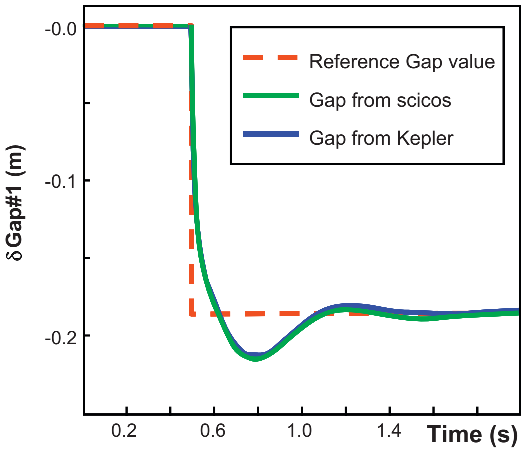

Fig. 4. Evolution of gap#1 for simulation under Scicos (green) and Kepler (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

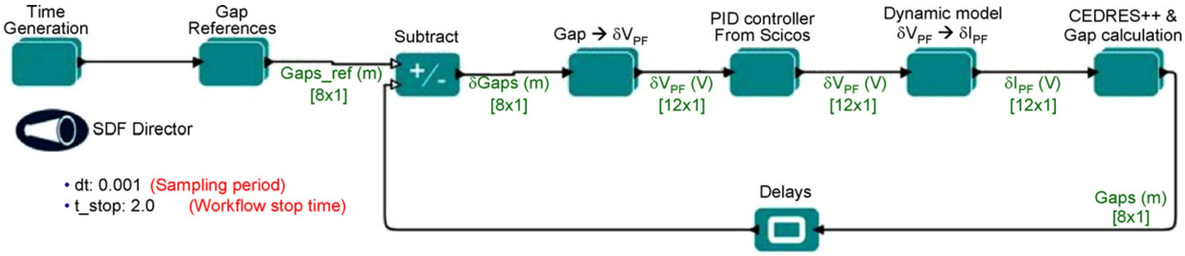

Fig. 5. Example of Kepler workflow (V_{PF} and I_{PF} are, respectively, the voltage and current in PF coils).

ing the plasma such as $\delta\psi = M_\psi\,\delta I_{\mathrm{PF}}$ (where δ_ψ is the flux variation in PF coils, and M_ψ is a 12 × 12 matrix).

The dynamic part of the model is given by the circuit equation: $\delta V = L\,\partial\,\delta I/\partial t + R\,\delta I$. The first step in the development of the controller consisted in the implementation of the resulting control oriented model onto the ScicosLab/Scicos control toolbox and in the design of a multi-input multi-output proportional-integral-derivative controller.

From the Scicos controller, a Kepler actor is generated using the C code generation functionality of Scicos and the fc2k tool. The details of these operations are provided in [14]. As a first step, to validate this new actor based on the Scicos controller, the control oriented model of the plasma derived from CEDRES++ and the dynamic part given by the circuit equation has been reproduced in Kepler. A perfect agreement is observed between simulations performed both under Scicos and under Kepler with the imported controller (Fig. 4). It demonstrates successfully that a controller developed under Scicos can be used on the ITM-TF simulation platform. Recently the CEDRES++ code has been added to the physics and engineering model library available for Kepler applications. Thus the linear control oriented model has been replaced by the non linear free boundary equilibrium CEDRES++ actor (Fig. 5).

5. Conclusion

A GMFS has been set-up to comply with the needs of plasma discharge performance and safe tokamak operation. The project has started in 2008 and is closely linked to the ITM-TF effort and, in particular, the ITM-TF simulation platform based on the Kepler orchestrator tool. The controller itself is developed using a control toolbox tool and then imported in the form of an actor onto Kepler. The originality of this framework is that control workflows can be built ad libitum from a physics and engineering models library, which is provided by the ITM-TF. A first application of the GMFS has demonstrated the ability to develop a controller and to implement it successfully onto Kepler using only open source tools. This example therefore demonstrates the capability of the GMFS in providing an efficient framework in preparation of ITER operation. Both the GMFS and the ITM-TF simulation platform are nevertheless still under development. The future plans are to implement the “hardware in the loop” mode using the Tore Supra PCS as a test bed and to validate the entire functionalities of the GMFS.

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