Implementation of Plasma Simulators and Plasma Reconstruction Workflows in ITER's Integrated Modelling & Analysis Suite (IMAS)

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1. Introduction

The Integrated Modelling & Analysis Suite (IMAS) is the software infrastructure being built using expertise from within the ITER Members to support the execution of the ITER Integrated Modelling (IM) Programme. The principal objective is to provide the validated physics tools required for the successful execution of the ITER Research Plan. The infrastructure is based upon earlier work carried out within the EU [1,2] and centres around a new standardised representation of the data [3]. This Data Model, which is capable of representing both simulation and experimental data, is not restricted to ITER and indeed its applicability to other devices is an important element in facilitating the development and validation of tools and workflows on existing devices in preparation for their use on ITER.

2. Plasma Simulators

One of the primary workflow developments required to support the Use Cases associated with these activities is a predictive Plasma Simulator validated against experimental data. Plasma Simulators appear in many of the foreseen Use Cases associated with scenario design, pulse preparation and pulse validation. The competing requirements for performance and physics fidelity drives the need for a range of Plasma Simulators and workflow components that can be combined according to the specific Use Case needs.

High Modularity Transport Simulator (HMTS)

The High Modularity Transport Simulator (HMTS) is a Plasma Simulator in which all components communicate through Interface Data Structures (IDSs) defined in the IMAS

Data Model. It has been developed to serve as an example to support other activities and is based upon earlier EU EFDA-ITM/EUROfusion work. The initial version uses a prescribed plasma boundary and solves the 1-D transport equations in the plasma core for the poloidal flux, electron density and electron and ion temperatures. It makes the structure of the simulator fully transparent within the workflow and provides a standard method for coupling new components, which may be written in different programming languages. The HMTS is being combined with the EU-ETS to deliver a more comprehensive Plasma Simulator.

DINA

The DINA code [4] has been adapted into an IMAS workflow in which the controller is a separate IDS-compliant component that can also be used within the Plasma Control System Simulation Platform (PCSSP) [5] as part of co-simulations with IMAS. Predictive simulations for ITER, respecting engineering limits, have been performed for a complete cycle of the poloidal field circuit. At present, DINA is the only scenario modelling code that can simulate a full period of the ITER poloidal field (PF) system operation (including breakdown) and provide detailed analysis of engineering limitations during the simulation. Predictive simulations of the ITER 7.5MA scenario respecting engineering limits have been performed for a complete cycle of the poloidal field circuit using feedback and feed-forward control of the plasma current, position and shape with vertical plasma stabilization.

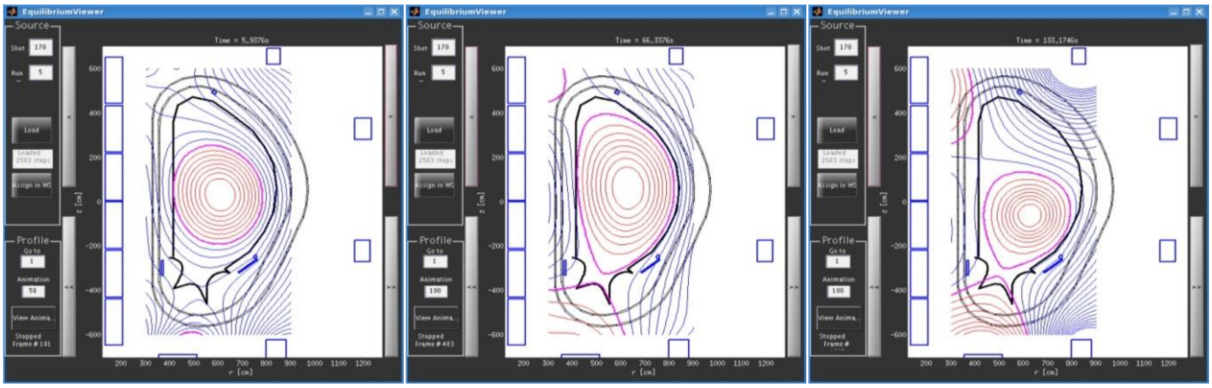

Figure 1: Examples of plasma equilibria at times 5.9s, 66.3s and 133.1s from the IDS database populated from a 280s DINA simulation of ITER

Further development of the DINA workflow will include a description of the separatrix plasma/neutral conditions and the coupling with external heating, fuelling and CD sources.

3. Heating and Current Drive Workflow

A dedicated Heating and Current Drive (H&CD) workflow to provide the sources for integrated transport simulators from all heating methods, i.e. electron cyclotron (EC), ion cyclotron (IC), lower hybrid, neutral beam injection (NBI), and nuclear reactions, including associated synergetic effects, has been adapted to IMAS based upon earlier developments within the EU-IM programme. The H&CD workflow offers a combination of solvers of varying degrees of physics fidelity and computation performance, enabling appropriate choices to be made depending upon the needs of the specific use case. The present implementation in IMAS includes the NEMO code [6] for neutral beam deposition, the CYRANO [7] and TOMCAT [8] codes for IC waves, and the RISK [9] and SPOT [10] codes for ion Fokker-Planck calculations. The workflow has been developed within the Kepler workflow engine [11], although the algorithm itself is workflow engine agnostic and could be implemented using other supervisory approaches such as the recent extensions to allow the direct use of physics actors in Python to support the development of Python workflows. The complete H&CD workflow has an extensive development history and has been associated with various other benchmark activities for EC [12], IC [13] and NBI [14] codes.

4. Data Access

To facilitate the development of device-independent workflows that can be validated on present-day devices ahead of ITER Operation, the IMAS data Access Layer has been augmented by Universal Data Access (UDA) technology which uses plug-ins to access and map data into the ITER Data Model. Such plug-ins are currently being developed for ITER, JET, MAST, WEST and the ITPA H-mode and confinement databases (following their migration to an ITER server). A remotely accessible and searchable central ITER database for reference simulations (both interpretive and predictive) is currently being designed and implemented. This is in parallel with the creation of a simple library of results from running IMAS-adapted codes and translating existing results into the ITER Data Model.

5. Data Processing

One of the primary requirements for interpretive analysis of ITER experimental data is the automated processing of diagnostic signals into physically consistent parameters and profiles. The ITER Project Requirements lays down the list of parameters to be measured, which are subsequently delegated to the various diagnostic systems capable of contributing, and spatial and temporal resolutions and accuracy are assigned. Diagnostics thus contribute to delivering the overall requirements rather than individual measurements which points towards an integrated (probabilistic) approach to determining measurement quantities and their uncertainties. A combination of results from distinct diagnostics is thus replaced by a combination of measured data to deliver measurement parameters with reduced uncertainties. While the details of this approach remain to be established the Integrated Modelling framework is designed to be flexible enough to handle all foreseen approaches.

6. Plasma Reconstruction and Live Display

In addition to displaying the Real Time reconstructions required by the PCS in the Control Room, the Live Display of data with IMAS will also be possible. Live Display can tolerate more latency which means it can also be more comprehensive in terms of data processing and interpretation. Tests are currently underway to demonstrate the streaming of experimental data, its processing and subsequent Live Display. The workflow chosen is a machine-independent interpretive equilibrium as the basis for a more comprehensive plasma reconstruction chain. IDSs generated from experimental data (JET and MAST) have been passed to EFIT++ to produce an equilibrium IDS. In a next step, other equilibrium codes will be used to demonstrate the interchange of components. An interactive Live Display, VIPER, using a web server that displays data as it becomes available has also been demonstrated.

7. Summary and Outlook

IMAS has been installed within the majority of the ITER Members and is being used to support ITPA activities including code benchmarking and validation. Sophisticated workflows, such as Plasma Simulators and those describing H&CD systems, have been adapted to IMAS and applied to ITER scenarios. The framework is considered sufficiently flexible to handle all foreseen approaches to the integrated (probabilistic) determination of measurement parameters (and their errors). The inclusion of UDA within the IMAS data Access Layer has allowed the fetching of IDSs directly from experimental databases and the demonstration of the first plasma reconstruction chain. An interactive Live Display in which signals are selected through a web interface has also been demonstrated.

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References

[1] G.L. Falchetto *et al.*, Nucl. Fusion **54** 043018 (2014)
[2] G.L. Falchetto *et al.*, 26th IAEA Fusion Energy Conf., Kyoto, Japan (2016), TH/P2-13
[3] F. Imbeaux *et al.*, Nucl. Fusion **55** (2015) 123006
[4] R.R. Khayrutdinov and V.E. Lukash, Journal of Comp. Physics, **107** (1993) 106
[5] M.L. Walker *et al.*, Fusion Engineering and Design **96–97** (2015) 716–719
[6] M. Schneider *et al,* Nucl. Fusion **51** (2011) 063019
[7] P.U. Lamalle, LPP-ERM/KMS Lab. Rep.101, Brussels (1994)
[8] D. Van Eester and R.Koch, PPCF **40**(11) (1998) 1949-1976
[9] M. Schneider *et al*, Nucl. Fusion **55** (2015) 013003
[10] M. Schneider *et al,* Plasma Phys. Control. Fusion **47** (2005) 2087–2106
[11] Kepler project: http://kepler-project.org
[12] L. Figini *et al.*, EPJ Web of Confs. **32** (2012) 17th Joint Workshop on ECE and ECRH
[13] R. Bilato et al, 20th RF Topical Conf., Sorrento (2013)
[14] M. Schneider *et al*, Proc. 42nd EPS Lisbon (2015) P2.159 ECA Vol. 39E