Progress in the ITER Integrated Modelling Programme and the use and validation of IMAS within the ITER Members

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Abstract. The ITER Integrated Modelling (IM) Programme will not only support the ITER Project in the development and execution of the ITER Research Plan (IRP) but also provide support for the design basis of the ITER facility during construction, in particular for diagnostics. Strategically, the ITER IM Programme is implemented using expertise and technologies developed within the ITER Members' research programmes with annual reviews by an Integrated Modelling Expert Group (IMEG) comprised of experts from all the ITER

Parties. The Integrated Modelling & Analysis Suite (IMAS) is the software infrastructure that has been developed in response to the needs of the IM Programme and which will support the requirements of both plasma operations and research activities. An agile approach is taken to the development of IMAS and a software management framework consisting of linked issue tracking, source code repositories and a continuous integration server to automatically build and regression test revisions has been established. It is essential that results generated for ITER are reproducible and so software hosting and rigorous version control are prerequisites and already ensured, whilst provenance tracking for handling inputs is still in development.

The unifying element of IMAS is its use of a standardized data model capable of describing both experimental and simulation data. This enables the development of workflows that can flexibly use different software components as well as being independent of the device being modelled. This makes IMAS an ideal framework for conducting code benchmarking exercises, such as that within the ITPA Energetic Particle Physics Topical Group on the calculation of fast ion distributions. In this paper, some of the initial software adaptations are presented to indicate the use, and consequent validation, of IMAS within the ITER Members. This has been facilitated by this year's release of a local installer for IMAS which has already allowed installation within the research facilities of the majority of the ITER Members including China, EU, India, Japan, Korea and the US. For the most part, these workflows are predictive in nature with interpretive workflows expected to follow from the development of plugins to the IMAS data access tools to securely read and map (remote) experimental data from existing devices into the standardised data model.

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 validation of IM tools and workflows on existing devices in preparation for their use on ITER.

To support the local installation of the IMAS infrastructure within the ITER Members and facilitate the development and validation of physics workflows, an installer has been developed to locally install and manage the core data access tools (Access Layer and Data Dictionary) and (optionally) the Kepler workflow engine and coupling tools (FC2K). The installations are versioned and configured using environment modules [4] which allows an administrator to install multiple versions and users to select between them.

The adaptation of many well-known codes from across the ITER Members to IMAS, including ASTRA [5], CORSICA [6], EFIT [7], ELITE [8], EPED [9], GACODE [10] (including TGLF, NEO, GYRO and TGYRO), TASK [11] and TRANSP [12] has started with the development of global translators to the ITER Data Model for each.

2. Plasma Simulators

One of the initial Use Cases targeted within the IM Programme is the development of a Plasma Simulator. Such a simulator appears in many of the foreseen Use Cases associated with scenario design, pulse preparation and pulse validation. A hierarchy of workflows with varying degrees of physics fidelity and computation performance is therefore foreseen.

2.1. 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. Figure 1 shows a top-level view of the HMTS workflow as implemented within the Kepler workflow engine [13].

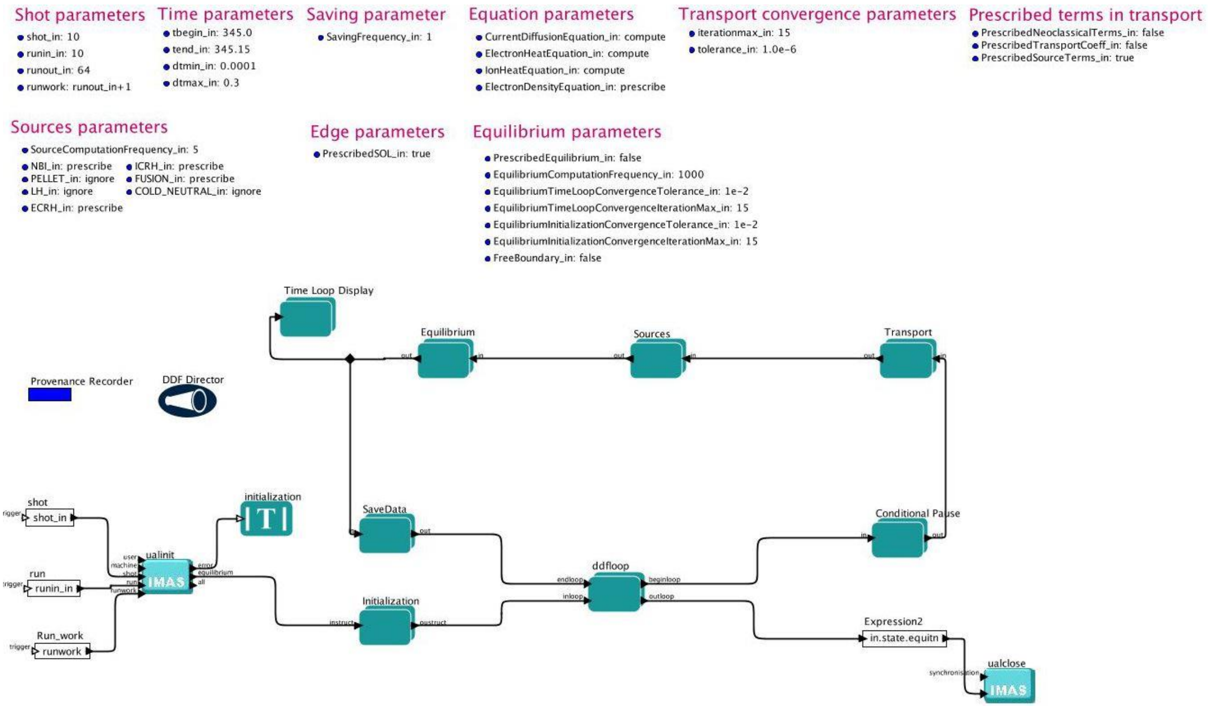

Figure 1: Top-level of HTMS workflow

2.2.DINA

The DINA code [14] 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) [15] 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. Building upon the development of an earlier modular version, DINA-CH [16], DINA has been integrated into IMAS to form a Plasma Simulator that can be used together with the Plasma Control System Simulation Platform (PCSSP) to support scenario and controller design.

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. The scenario was designed and simulated at the limits of the CS coil currents of ± 30 kA which corresponds to half of the maximum allowable value of stresses in the CS conductors, $\max(I \times B_{max}) \approx 270$ kAT. The simulation of the plasma transport featured a radiation model with beryllium (Be), tungsten (W), and neon (Ne) impurities taken into account when the value of plasma current was higher than 1.5 MA. All phases of the PF system operation were modelled: initial magnetisation of the CS, gas breakdown with ECRF assist and central-inboard plasma initiation; plasma current ramp-up with early formation of divertor configuration; plasma current flattop with 5 MW of ECRF heating; plasma current ramp-down in divertor configuration, and final termination of the currents in the CS and PF coils (without plasma). In these simulations the stabilization of plasma vertical displacements was performed by feedback loops VS1 and VS3. Low frequency noise with a uniform spectrum and RMS value $\langle dZ/dt \rangle$ = 0.6 m/s in the frequency band [0, 1 kHz] was "injected" in the "diagnostic" signal dZ/dt used in the feedback stabilization of the plasma vertical displacements. In Figure 2, plasma equilibria at different times during the DINA simulation are plotted using an EquibriumViewer tool that was also developed to interface to the IDS database.

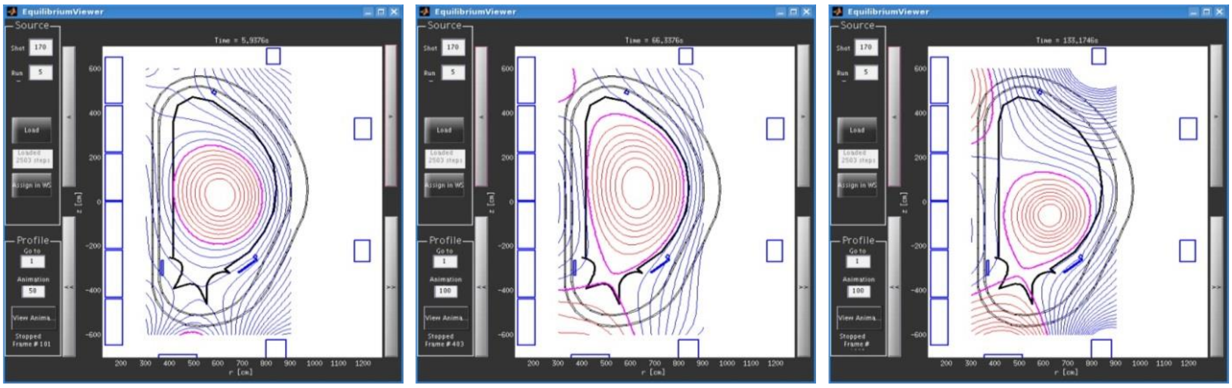

Figure 2: Examples of plasma equilibria at times 5.9s, 66.3s and 133.1s from the IDS database populated from a 280s DINA simulation of ITER

Further development of the DINA workflow will include additional modularization, including allowing transport and core plasma sources to be treated as external components.

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 [17] for neutral beam deposition and the RISK [18] and SPOT [19] codes for ion Fokker-Planck calculations. The NUBEAM [20] code is also currently being adapted for use in this and other workflows, including the benchmarking activity on fast ion distributions within the ITPA Energetic Particle Physics Topical Group which this workflow facilitates.

The workflow has been developed within the Kepler workflow engine [13], although the algorithm itself is workflow engine agnostic and could be implemented using other supervisory approaches. The complete H&CD workflow has an extensive development history and has been associated with various other benchmark activities for EC [21], IC [22] and NBI [23] codes.

3.1.NBI benchmark using IMAS

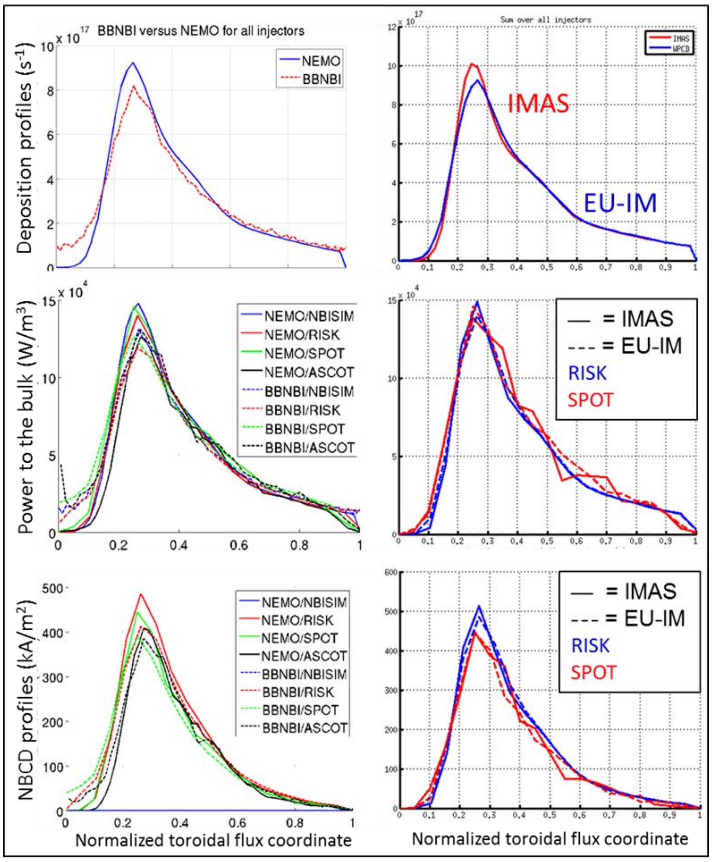

Figure 3: Result of the NBI benchmark using the H&CD workflow in EU-IM (left figures) and IMAS (right figures) frameworks for the ITER baseline scenario for the off-off neutral beam configuration. Top / middle / bottom figures show the deposition profiles, power to the bulk profiles and NBCD profiles respectively.

NBI modelling consists of combining a deposition code for the fast neutral beam attenuation and ionization with a Fokker-Planck solver simulating the dynamics of the NBI ions. Two deposition codes, the BBNBI [24] Monte Carlo code and the NEMO narrow beam model, associated with four Fokker-Planck solvers, ASCOT [25], NBISIM [26], RISK and SPOT, have been benchmarked within the EU-IM and IMAS frameworks. ASCOT and SPOT are Monte Carlo codes offering a high level of accuracy including finite orbit width (FOW) effects, whereas NBISIM is a simple 1D analytic model and RISK is based on a finite element resolution of the Fokker-Planck equation, both providing fast simulations but neglecting FOW effects. This flexibility in choice of components allows the workflow to be tuned according to the required balance of fidelity versus computational performance. This allows the workflow to be re-used for different purposes within different higher-level workflows.

The results of the NBI benchmark involving the above codes within the EU-IM [23] and IMAS frameworks are presented in Figure 3, covering all possible combinations between deposition and Fokker-Planck codes, for the ITER baseline scenario, with a comparison between EU-IM and IMAS frameworks. The results show good overall agreement between the physics models. Discrepancies arise for neutral beam current drive (NBCD) when FOW effects are not included in the Fokker-Planck calculations, i.e. for RISK and NBISIM, where the NBCD is overestimated by around 20% compared to SPOT and ASCOT. This shows that FOW effects are necessary to describe neutral beam current drive in the ITER baseline scenario but can be neglected when calculating the power deposition profiles.

4. Fast ion modelling

To calculate the fast ion power flux onto plasma facing components (PFCs) due to the use of the ELM control coils and other symmetry-breaking contributions to the magnetic field, the LOCUST-GPU code [27] has been explicitly developed for IMAS. In common with other codes of this type, it uses a Monte Carlo approach which necessitates following vey many ions in order to calculate the power and particle flux footprints onto small-scale in-vessel components with low statistical noise. By utilising the independence of the fast ion orbits the problem has been cast onto GPU technology, where it has been possible to determine the fast ion power flux (including statistical error) onto in-vessel components such as those under the divertor dome and shown in Figure 4 with unprecedented accuracy.

The complete workflow (validated against earlier ASCOT calculations) includes calculations of the plasma response by MARS-F [28] to the applied 3D fields which is found to have a significant influence upon the number of fast ions impacting PFCs and thus is very important to be retained.

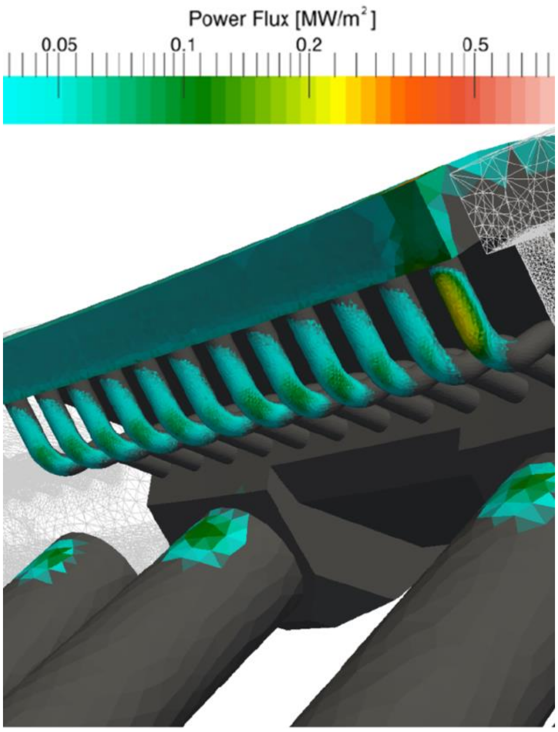

Figure 4: Fast ion power loading to the ITER divertor under-dome components for 33 MW of 1 MeV HNB into 15 MA flat-top H-mode with 90 kAt of n = 3 ECC field applied (incl. n = 6 sideband) including plasma response from MARS-F.

5. Modelling the Plasma Edge and Scrape-Off Layer

The workhorse tool for divertor design and plasma edge modelling at ITER has been the SOLPS code suite [29]. A new version of this software, SOLPS-ITER [30], has been developed and a new run environment created to support its use within IMAS [31]. For the purposes of this implementation, new IDSs have been developed that provide a full description of the tokamak edge plasma and makes use of an underlying Generalized Grid Description (GGD) that allows for computational meshes of arbitrary complexity. A new user interface (SOLPS-GUI) is also available to launch, monitor and archive runs, as well as a Paraview-based data analysis tool which has been prepared to examine runs in full detail.

6. Installation, Use and Validation of IMAS within the ITER Members

The development of IMAS installation tools has facilitated the installation of IMAS within the research facilities of the majority of the ITER Members including China, EU, India, Japan, Korea and the US.

6.1. Installation and use of IMAS on WEST (EU)

The WEST tokamak [32], planned to start operation in autumn 2016, will make use of IMAS for its plasma reconstruction chain and to offer external collaborators remote access to its experimental and simulated data using the IMAS Data Model. For these purposes, equilibrium reconstruction, profile fitting and visualisation tools have been developed.

Equilibrium reconstruction makes use of EQUINOX [33] which has been adapted to

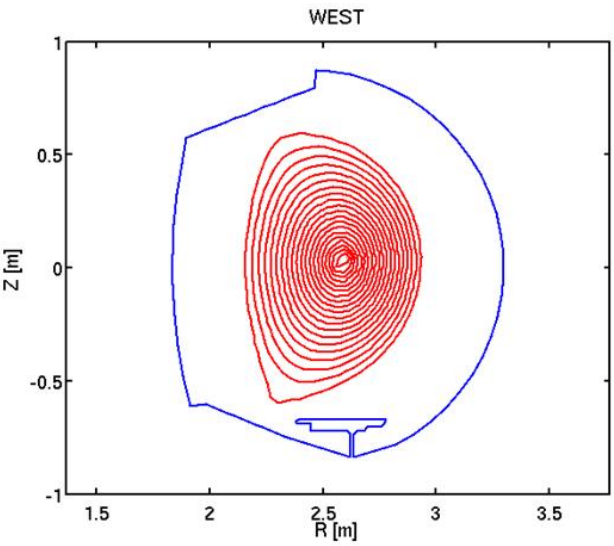

Figure 5: Closed flux surfaces of a WEST plasma equilibrium (red contours) as reconstructed by the EQUINOX code from synthetic magnetics measurements. The blue line is a simplified contour of the surfaces of the in-vessel components closest to plasma.

IMAS and will initially be constrained by magnetics measurements only. A first test of equilibrium reconstruction has been carried out using synthetic magnetic data generated from a WEST equilibrium computed predictively by CEDRES++ [34]. The magnetic data (both static data describing the position of the magnetic sensors and the measured values) are passed to EQUINOX in the form of the magnetics IDS, and the equilibrium generated by EQUINOX is output as an equilibrium IDS (Figure 5). This equilibrium is then used for mapping various measured profiles onto the flux surface and magnetic field maps, which is done using a machine-generic profile fitting tool with I/O in IMAS format (Figure 6). An IMAS-compliant equilibrium interpolation library has also been developed to evaluate with accuracy the values of the poloidal flux, toroidal flux, as well as the magnetic field components at any point, taking into account the magnetic field ripple in a perturbative manner. This forms the basic set of machine-generic tools for reconstructing plasma profiles using the IMAS Data Model.

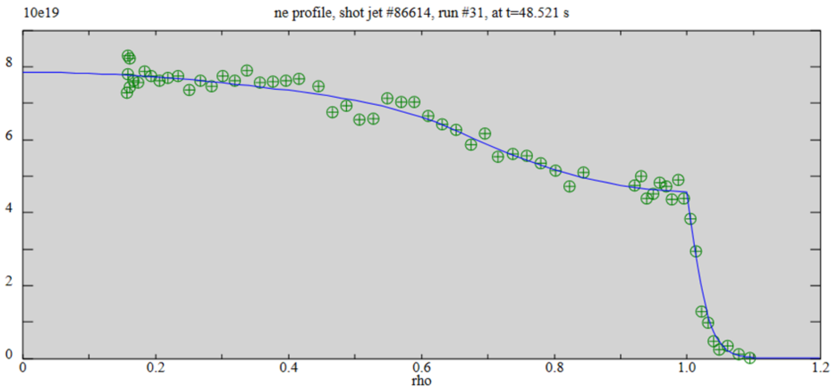

Figure 6: Fit of the electron density profile for a time slice of a JET shot (blue line), as a function of the normalised square root of the poloidal flux, obtained with a profile fitting tool developed for the IMAS Data Model. The fit was constrained from High Resolution Thomson Scattering (green crossed circles) measurements.

7. Installation and use of IMAS at NFRI (Korea)

IMAS and the Kepler framework have been successfully installed and tested at the National Fusion Research Institute (NFRI) in Korea. As a simple application, IMAS has been used to develop an initial magnetization module which evaluates the set of optimum poloidal field (PF) coil currents in ITER. The module is based on the quadratic programming algorithm [35] where the total magnetic energy of the coil system is minimized. The code is made fully compatible with the ITER Data Model and utilizes the Kepler workflow engine. Figure shows a contour plot for the magnetic field calculated using this initial magnetization module for an inboard start-up scenario in ITER.

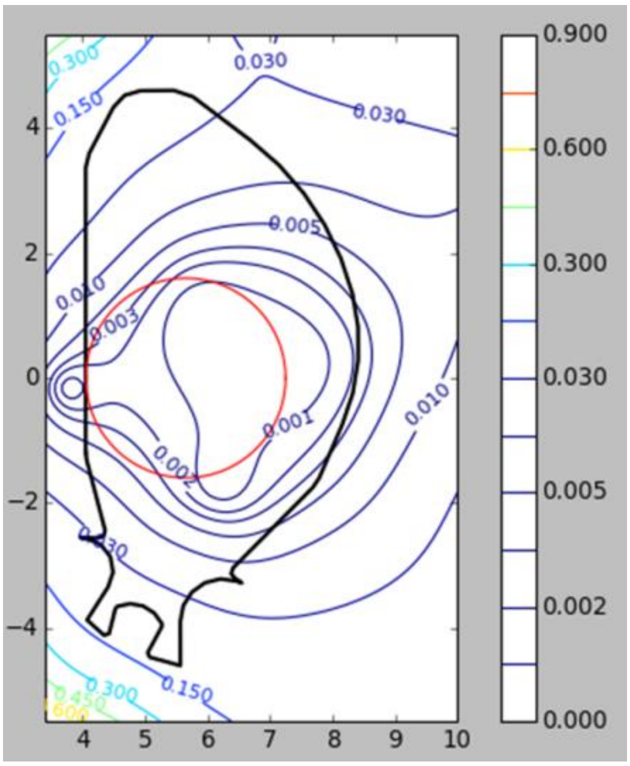

Figure 7: Magnetic field contours in ITER calculated for inboard start-up scenario

8. 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 that describing H&CD, have been adapted to IMAS, whilst new workflows, including predictive Plasma Simulators capable of describing ITER, are being developed within the Members' R&D facilities.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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