ITER Organization-EUROfusion Collaboration

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ITER organization

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china eu india japan korea russia usa

Support for ITER's Integrated Modelling & Analysis Needs

ITER's needs are driven by various use cases, chief amongst which are:

- Preparation of ITER scenarios for carrying out ITER Research Plan
- Support for validation of ITER systems and components, including actuators, diagnostics and controls
- Experimental data processing and analysis
- Interpretative modelling of ITER pulses and physics studies

These different needs motivate a range of plasma simulation capabilities, the pinnacle of which, in terms of physics capture (and thus validation needs), is a high-physics-fidelity plasma simulator capable of modelling complete integrated ITER scenarios, including PF circuits, free-boundary equilibria, core-pedestal-SOL and plasma-wall/target interactions

Also motivates the development of a rigorous capability to infer plasma properties from experimental measurements and their uncertainties

Collaborative activities to address scientific topics and scientific gaps in the physics basis of ITER assembly, scenarios, plasma measurements, analysis and simulations

The following topics have been agreed to be covered over the period 2026-2027

- Cooperation Agreement between EUROfusion and ITER Organization signed at IAEA FEC last year
- Implementing Agreement not yet actually signed because other topics are still be converged, but the physics gap part is finalized

A mandatory requirement for joint software development is that, when completed, this is made available under an open-source licence

Some topics related to model application and validation may be supported by IO postdocs

Some activities may be financial supported by the IO, and if so, will be carried out under separate implementing agreements or contracts

IO-EUROfusion collaborative activities involving JT-60SA are not described here

HFPS improvements, i.e. Improvements to "high fidelity plasma model"

Development of a transport model applicable for burning plasmas including energetic particles and models validated at high β (electromagnetic effects)

Current transport models tuned to existing conditions rather than those expected in ITER.

Bridge gap to wall

Core-edge modelling currently uses JINTRAC (JETTO-EDGE2D)

Flagship boundary model SOLPS-ITER, in its Wide Grids form, supports unstructured grids up to the first wall. Couple SOLPS-ITER with core plasma model → Previously demonstrated as part of work by EFDA ITM Task Force. Enable accelerated SOLPS-ITER runs using techniques from EDGE2D.

Develop wall inventory model in SOLPS-ITER

This will be used to perform self-consistent simulations of edge plasmas and wall inventory.

Use of MUSCLE3 for persistent actors

All these improvements to be reported by December 2027 to support revision of ITER Research Plan, if needed.

Development of analysis workflows for experimental data

All these activities support the integrated data analysis of ITER plasmas (and those of other machines) and the validation of the workflows. The areas of priority from IO's point of view are listed below.

The detailed strategy for their implementation, including the required level of support by the IO is to be discussed at the first progress meeting in June 2026.

- **Development of workflows for core plasma profiles for electrons and ions (density/temperatures) and impurities (W, B, Ne, etc.)**
- **Development of digital twins for diagnostic systems and coupling with HFPS: Thomson Scattering (core and edge) and core X-ray crystal spectrometer**
- **Development of tools using Kalman Filters for model-based estimation of plasma equilibrium, plasma profiles and physics parameters**

This work is to support the integrated data analysis of ITER plasmas and the validation of the workflows by the end of 2027. An initial version of the last workflow is ready and has been demonstrated with TCV data.

Use and validation of analysis workflows for experimental data

The areas of priority from IO's point of view are listed below. The detailed strategy for their implementation, including the required level of support by the IO will be discussed in June 2026:

- **Use and validation of equilibrium analysis workflows**
  - Requires mapping of appropriate data (incl. Machine Description and dynamic data)
- **Use and validation of core density and temperature workflow**
- **Use and validation of core plasma impurity density workflow**
- **Use and validation of Kalman-Filter supported workflows**

Validation of SOLPS-ITER wide grids and ensuing W source/transport (ERO 2.0/WallDYN)

The validation of W wall source is very high priority.

Emphasis on validation of far-SOL transport model (i.e. identified dependencies of required transport coefficients on plasma conditions and across devices) and impact on W wall source and transport.

This activity is already on-going at TCV through an IO-F4E-SPC collaboration for far-SOL transport but should be extended to devices with a W wall.

Main focus of this activity for ITER is on extending the initial TCV effort on far-SOL transport to ASDEX Upgrade (and WEST, if possible) using edge transport codes with grids up to the vessel walls (SOLPS-ITER wide grid, SOLEDGE3X, …) since studies in these devices provide additional validation for the W wall source and SOL transport.

The result of this work in final form should reported by December 2027.

Validation of HFPS, DINA-HFPS plasma simulators

This area includes a wide range of activities all of interest to ITER. Some support from IO can be provided for specific topics. Depending on the level of support that IO can finally provide, the items below may be implemented or not in the 2026-2027 workprogramme, or done on a different timescale.

Validation of DINA-HFPS full plasma scenario simulation

First steps of this activity are already on-going at TCV under IO-FE4-SPC collaboration and could be extended. Of higher priority to ITER would be to apply DINA-HFPS to ASDEX Upgrade (and possibly WEST) and validate it for an ITER-relevant scenario such as a hybrid H-mode.

Validation of HFPS W limiter plasma simulations

This requires well diagnosed plasmas on W limiters in present experiments (WEST, AUG) to validate predictions to ITER. Support by IO staff can be provided for a limited validation exercise with results to be reported by December 2027.

Validation of HFPS and DINA-HFPS

Validation of HFPS in W tokamak scenarios

This aims to validate all aspects of HFPS except those related to free-boundary evolution. This is an on-going effort in WEST that could be expanded considering the availability of gyrotrons at WEST. Similarly, the same effort could be implemented in AUG with more relevant scenarios for ITER, if the more ambitious DINA-HFPS above activity cannot be implemented. The result of this work should be reported by December 2027.

Validation of HFPS in Ne seeded high-performance JET plasmas

This aims to validate all aspects of JINTRAC except those related to free-boundary evolution in plasma conditions relevant to ITER such as high-performance, small ELM, Ne seeded H-modes at JET in DD and DT. Some efforts along this line have taken place but could be expanded considering a wider set of plasmas at JET and, possibly extending the study to include AUG and WEST. The result of this work should be reported by December 2027.

Map data to support use and VVUQ of IMAS software

Recall IMAS software is that which will be used on ITER but is also openly available for use on other machines (IMAS data model is specifically device independent) where it can supplement local software and allow sharing of maintenance / development burden

Real data (warts and all) is essential for testing and validating IMAS codes and workflows

Want to compare software planned to be used on ITER with that currently used on today's machines, e.g. equilibrium reconstruction: quality of fit, ability to parameterize profiles, speed, etc.

Want to quantify domain over which "software acceptably describes experiment" to provide guidance on its domain of applicability to ITER

→ Recall Monday's discussion on how to do this and need to define what this metric looks like

Move emphasis from developing → validating → using physics software

Move from software development to software use

- Shift focus from developers to users to power users
  - These are probably not the same people – there is probably a benefit for software validation if they're not (no conflict of interests)
  - Power users should follow advanced trainings and contribute to further developments as stakeholders and act as contact persons / representatives for users
- Need user documentation (not just developer notes) and training material
  - Aside from software usage driving improvements, including to IMAS data schema, also provides an opportunity to start training the next generation of users who will use this software before the start of ITER operation (e.g. for scenario design) and during it
  - Can also be used to support creation of agentic AI models – IO plan to start working on this in 2026, using LLMs to bootstrap them from the code base + introspection + explorative code runs
- Make physics software easier to install (improved portability) and use: packaging and distribution
  - EasyBuild / EESSI, PyPI, Conda, Docker, RPMs,...

After Open Source, Open Data?

After making IMAS software open source the IO has started making IMAS datasets publicly available on Zenodo to support modelling ITER (towards F**A**IR)

- ITER MD data: https://zenodo.org/records/17113713
- ITER simulations: https://zenodo.org/records/17062700

Publish datasets along with journal publications and benchmarks from ITPA groups

Publishing openly at least one IMAS dataset (machine description + dynamic signals) for each device would improve a lot code testing and gathering feedback

And whilst open source is a good first step, should also make it easy for people to contribute back – this means the ability to self-create a local account (*ala* GitHub, etc.), raise issues, contribute to discussions, push proposed changes (to a personal fork) and raise a PR

And even though ITER is nominally 2D...

The IMAS data model already contains some non-axisymmetric elements (e.g. `coils_non_axisymmetric`) but it could be extended, not by the IO, but ideally by stellarator community (perhaps even in the private sector), to better support objective comparisons across tokamak-stellarator worlds

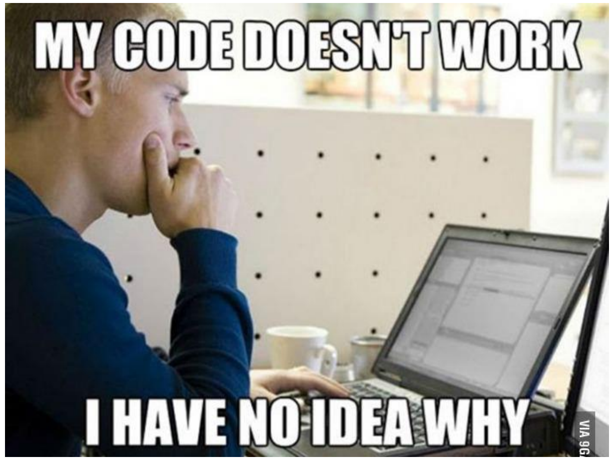
This would also enable stellarator codes to be more easily applied to tokamaks, supporting their validation and benchmarking, and potentially allowing the sharing of their maintenance burden across a larger community

Take advantage of AI to help visualise the future

A revolution has recently occurred

- Software written by AI can start to be trusted - not necessary to check everything
  - Should still regression/unit test as for any developer though
- AI can help with mapping data and adapting software to IMAS since it understands the IMAS Data Model
  - The IO have been successfully working with TCV to demonstrate this
- And if we're ambitious (and we should be) can think of developing an AI world model for fusion plasmas: Trained on existing experimental plasma data (from tokamaks and stellarators) and their response to external actuator inputs to learn how plasmas behave
- EUROfusion / the fusion community has data that can be used to start training such models, but are we willing to all work together to build such a capability? Could be very useful for deciding what a future FPP should look like in FP10....
  - This is a very large task that should be broken down into smaller parts and likely needs collaborative input from experts outside existing skills base

Previously



Now