ITER-Related Research Gaps

Linking ITER and EUROfusion Theory & Simulation Needs

Simon Pinches, Section Leader, Plasma Modelling & Analysis

EUROfusion E-TASC General Meeting

11 - 15 November 2024

iter

china eu india japan korea russia usa

Integrated Modelling

- ITER's plasma simulation needs are driven by various use cases, chief amongst which are:
  - Preparation of ITER scenarios for ITER Research Plan and experimental campaigns
  - Support for validation of ITER systems and components, including actuators, diagnostics and controls
  - Design of specific pulses to support execution of ITER Research Plan
  - 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, core-pedestal-SOL and plasma-wall/target interactions

Different types of plasma simulators

F. Felici, EFPW 2023

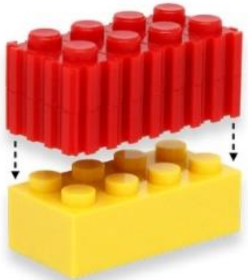
High Fidelity Plasma Simulators	• Uses comprehensive (potentially time-consuming) models to account for all possible physics to simulate plasma behaviour	ASTRA, ETS, DINA, JINTRAC, TRANSP
Flight Simulators	• Test and validate controllers in closed loop simulations • Strictly restricted to taking input from diagnostics and simulating plasma state from requests sent by the PCS	FENIX
Pulse Design Simulators	• To design scenarios → write optimal pulse schedule, using closed or open loops, with or w/o controllers • Mostly solves an inverse problem for discharge optimization • Compare to OLCs (physics and plant systems) • Resulting pulse schedule can be used: 1) As input to other simulators (e.g. HFPS) 2) For plasma operation	METIS
Real-Time Simulators	• Faster than real-time • Test PCS controllers (state estimates, event detection...)	RAPTOR, RAPDENS, PCSSP

PCS: Plasma Control System

OLCs: Operating Limits and Conditions

Plasma Simulator Platform

- Given that at ITER the intention is for all required simulators to be adapted to use IDSs to represent input / output data, there is a natural opportunity to enable a hierarchy of simulators within a single platform (application)
- Enables flexibility in terms of common modelling with a set of tools
  - Direct comparisons between simple/fast and slower/detailed models
- Common data representation (IDSs) brings capability in terms of
  - Comparing simulations
  - IDS-based check-pointing would allow restart with compatible simulators and thus change in physics models for times of interest
- Individual plasma simulators can have varying degrees of model granularity and thus flexibility (performance vs. physics fidelity)



→ Strategy is thus not to commit to a single simulator but to remain agile

IMAS Simulator Platform

- Simulator Platform provides a common interface to managing runs
- Should not constrain development of individual simulators
  - JINTRAC-DINA, ETS, ASTRA, PDS, etc.
- Provides a common user interface to individual simulators
  - Simulators (workflow & components) may still have their own specific needs
- Supports integration of other simulators
  - E.g. Energetic stability workflow (EP-Stability-WF)
- Support links with database of simulations (SimDB)
- Still possible to run individual simulators as stand-alone workflows

HFPS based on DINA-JINTRAC

- Current HFPS development is based on integration of
  - JINTRAC (core-edge-SOL transport with sources and exhaust, and kinetic control)
  - DINA (free-boundary equilibrium evolution and magnetic control)
  - H&CD workflow (heating and current drive physics)
  - and implementation of new features (2D edge grid evolution, W wall source, etc.)
- Desire to improve fidelity of edge model in HFPS
  - EDGE2D: Allows end-to-end integrated ITER simulations in ~1 month
  - SOLPS-ITER: More physics but too slow for time-dependent ITER cases
- NB. This is the *only* integrated modelling workflow that is capable of time-dependent coupled FBE core-edge-SOL transport simulations

S.H. Kim, B. Kim, F. Köchl, J. Lee, F. Poli, G. Suarez Lopez

Recommendations from ITER Council STAC

- The STAC recommends that the IO and Member communities work together to carry out a coordinated program of model validation, coupled with present-day experiments and all phases of the ITER Research Plan in order to maintain a predictive capability for later phases and future fusion devices.

Recommendations from ITER Council STAC

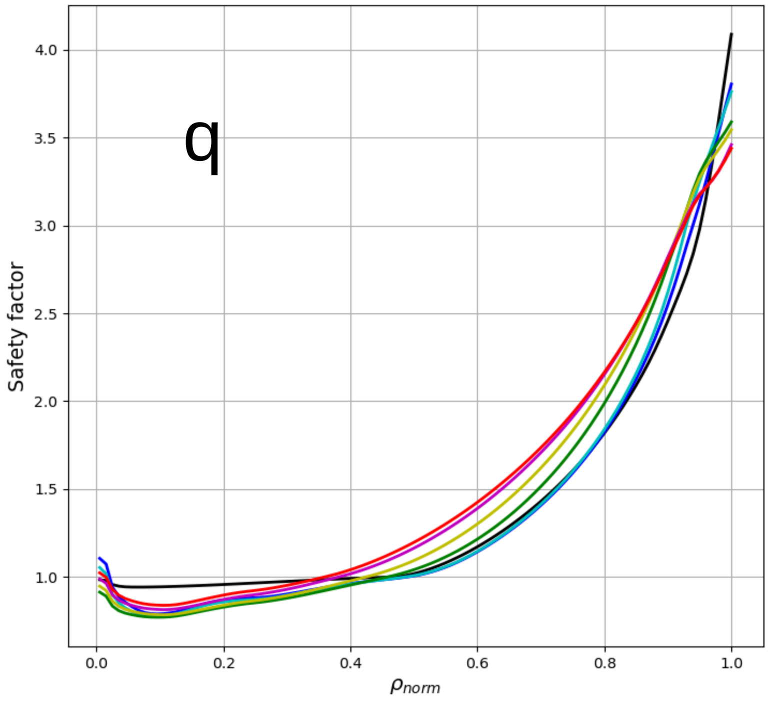
- The STAC recommends developing a strategy for the validation of tungsten transport codes (code-to-code validation and validation with experiments) to reduce uncertainties in the ITER transport regime, which should cover all discharge phases (current ramp-up, limiter configuration, diverted phase, steady-state phase, ramp-down phase, and termination).
  - Need simplified models for W wall sources
  - Improved transport models for SOL / far-SOL
  - Transport with discrete ELMs (particularly at low Ip in SRO) as well as in RMP-suppressed and no-ELM regimes

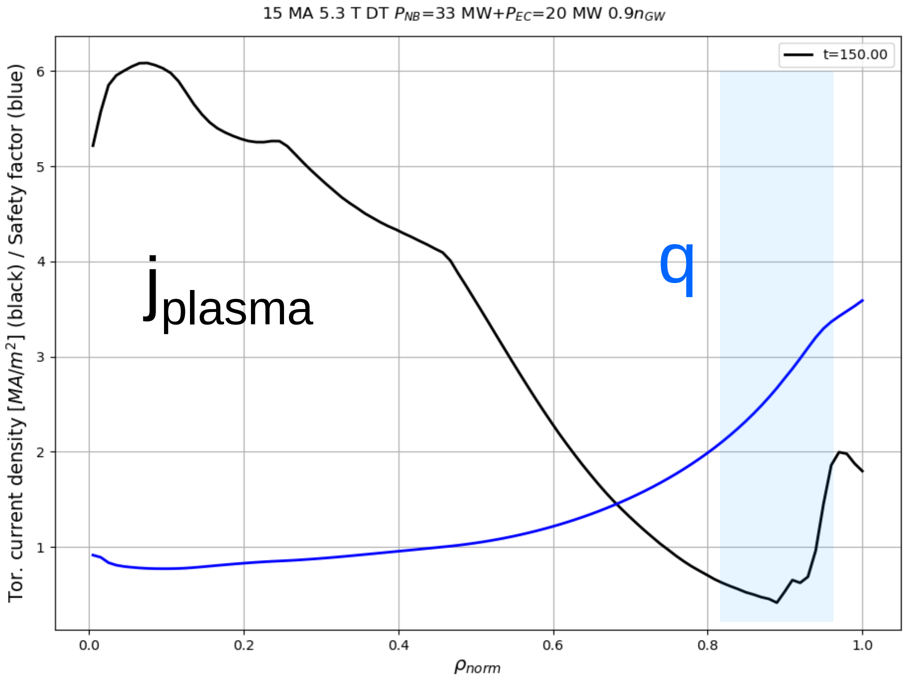
Recommendations from ITER Council STAC

- The STAC notes the IO efforts to simulate the current ramp-up during the tungsten limiter phase and the evolution of tungsten, which is potentially self-regulated. However, MHD stability and its effect on the tungsten transport in these current ramp-up discharges should be included in the analysis and modelling.
  - Stability models of hollow-current profiles in ramp-up and in H-mode edge

Extension of t_{burn} from ~ 50 s to ≥ 300s (planned for FPO-4)

- ITER Q = 10 j(r) profile evolves over times scales > 100 s → Impact on MHD (& EP) stability (à la DIII-D) and core transport (s = r/q dq/dr)
- Active MHD control (ECH r_{UL} = 0.8-0.88) or passive schemes (Poli NF 2017, Turco NF 2024) need to be explored to extend Q ≥ 10 burn beyond 50 s





Recommendations from ITER Council STAC

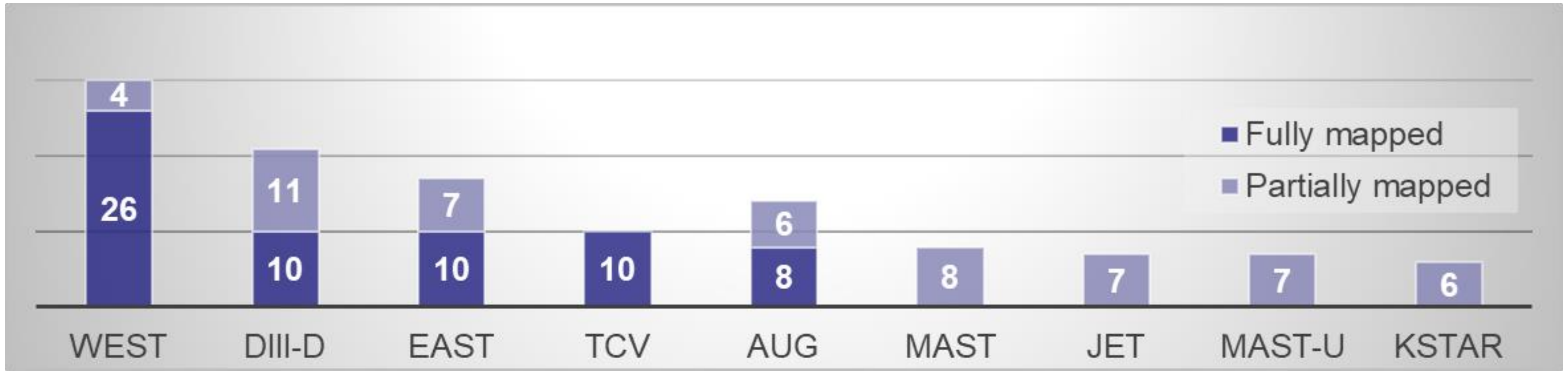
- The STAC recommends carrying out predictive modelling of first wall (B and W) erosion migration, and deposition in radiative (with light impurity seeding, e.g. neon) ITER H-mode plasmas (w and w/o RMPs, RISP) with the extended grid obtained plasma backgrounds reaching up to the wall.
- The STAC recommends performing dedicated modelling of RF-induced W sources with the new plasma backgrounds and common assumptions about far-scrape-off-layer (far-SOL) profiles and light impurity fluxes (e.g. neon).
  - Related to this are models for W control with auxiliary heating (core W transport) most likely needed in L-mode

Reduced turbulent transport model for burning plasmas

- Fusion power production depends upon fuel densities and temperatures in central region
- Current turbulent transport models are tuned to existing machines and give very different results for different choices of spectrum and saturation rules
  - Recall presentations by H. Zohm and poster by C. Bourdelle
- Robust predictions needed to support refinement of ITER Research Plan
- Motivates development of a new electromagnetic transport model that includes energetic particles and is applicable to all ITER operating phases

Code Validation (Models and Workflows)

- Want to validate capabilities (models and workflows) in terms of their ability to describe the real world to gain confidence for ITER applications
- Validating thus involves comparing with the real world and needs experimental data
- For models and workflows in IMAS, data is represented by IDSs
- Status from a survey last year (using different tools) of mapping data to IDSs

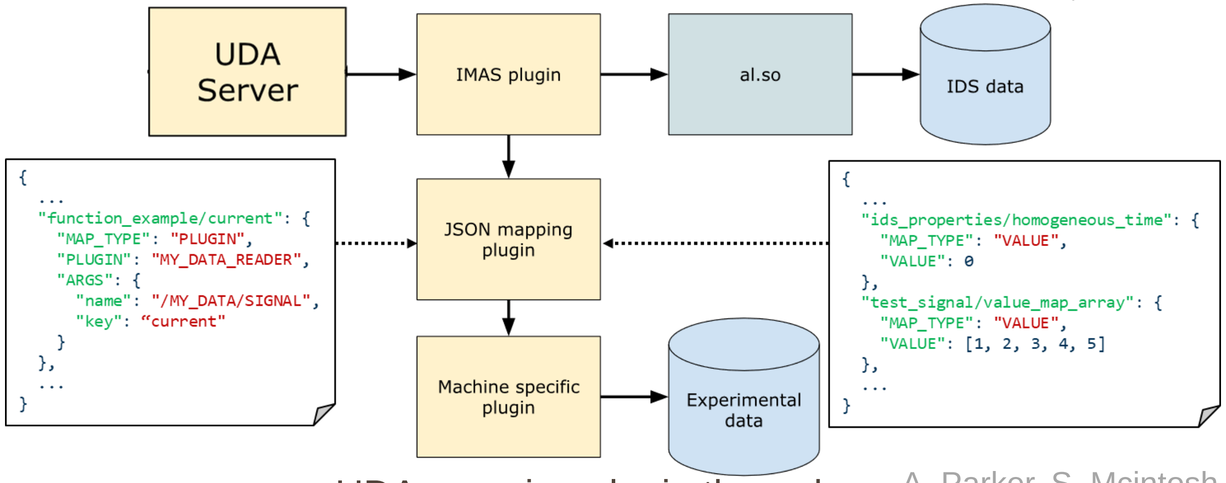


- For validating IM workflows, key IDSs expected to include
  - equilibrium, core/edge_profiles, pf_active/passive, Machine Description data

Mapping Experimental Data to IDSs

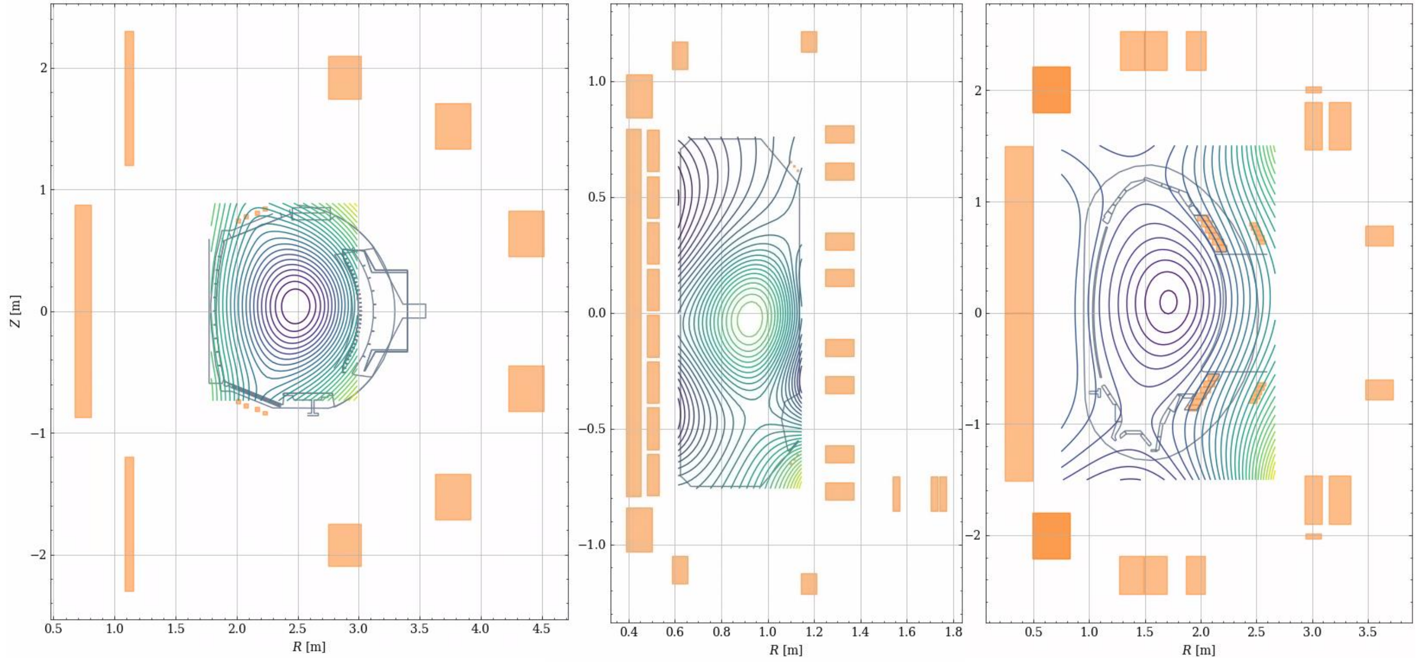
J. Hollocombe, A. Parker

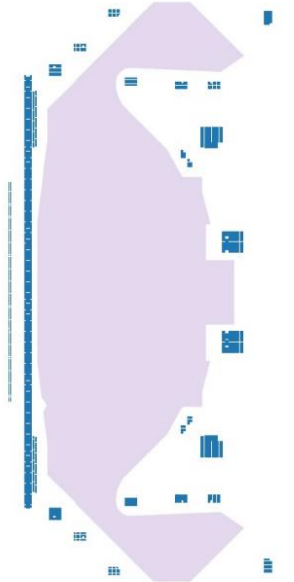
- Experimental data mapping always machine-specific
- In addition to providing remote access to data, UDA has a flexible JSON mapping plugin that can help map experimental data to IDSs



UDA mapping plugin through the generic JSON plugin

A. Parker, S. Mcintosh





Example of MAST-U Machine Description obtained from UDA mapping

Information and training available at

https://indico.iter.org/e/udamappings2023

Validating IMAS data interpretation pipelines for ITER

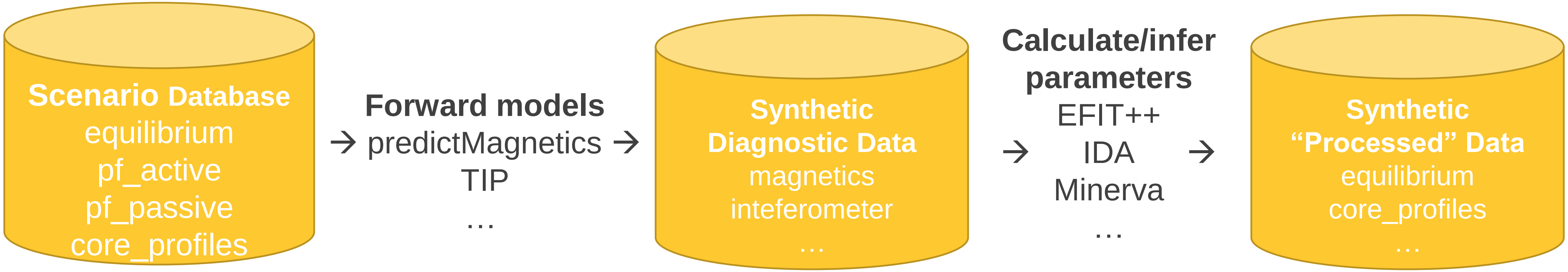
Map existing experimental measurement data to IDSs and interpret using IMAS workflows

e.g. `magnetics`, `interferometry` → `equilibrium`, `core_profiles`, etc.

- Develop data processing workflows (→ Live Display) and test real-world robustness to uncertainties
- Benchmark with existing (local) tools and approaches

Use diagnostic forward models with predictive plasma simulations to create synthetic experimental data

- Can compare calculated / inferred parameters with original simulation database



To support Bayesian inference of plasma parameters, diagnostic models must be performant (many calls)

Undertake performance analysis of software stack → Make improvements and eliminate bottlenecks

Proposed TRL definitions applicable to IMAS components

TRL9 Software routinely used for research operations and meets use case performance requirements.

TRL8 Software functionally integrated into the production system at ITER.

at ITER

TRL7 Software tested and validated on extensive data from relevant experiments. Complete documentation.

TRL6 Software tested and validated on selected data. Integration tests in place.

validation

TRL5 Software verified. Processes for maintaining software quality in place, e.g. CI testing.

TRL4 IMAS interface available for isolated testing. Source code is revision controlled.

IMAS

TRL3 Model implemented as software with limited user/developer documentation.

TRL2 Model identified and documented but not yet in the form of usable software.

TRL1 Specific need identified, but no model available.

Make physics software easier to install

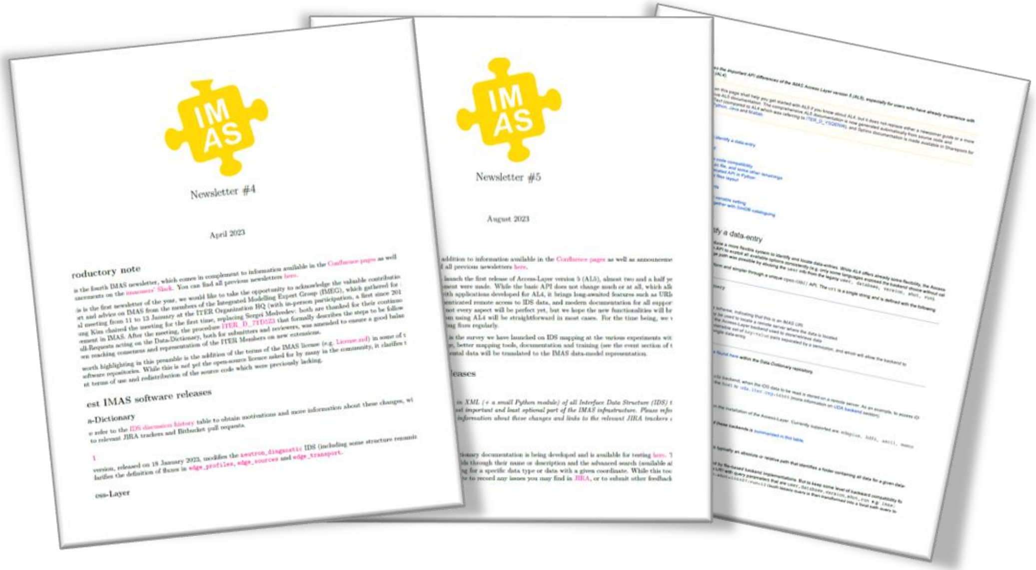
- Software is validated through use, so make it easy to use!
- Make software easy to install by using standard mechanisms wherever possible
  - `pip install`
  - `configure; make; make install`
  - `cmake`
- Install into standard directories under a given install prefix (bin, lib, etc)
- Specify required and optional dependencies, and use standard system tools like `pkg-config` to locate them at compile time
  - I.e. Improve software portability

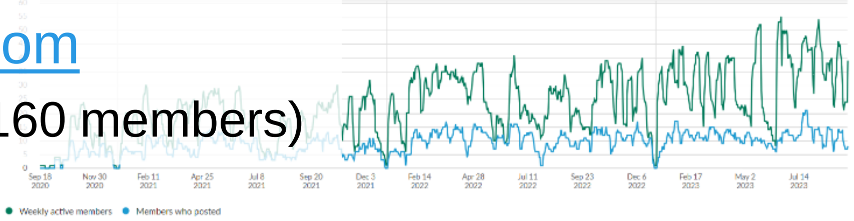
Open Source Software

- The ITER Organization is in the final stages of approving the release of all its Generated Intellectual Property (GIP) in IMAS software as open source
  - Where this software includes Background Intellectual Property held by third parties, then agreement will be sought from the rights holder
- Software hosting will move to GitHub and use the issue tracking tools there, GitHub actions for CI/CD, readthedocs for documentation, pypi, conda, etc.
- The initial proposal is CC BY-ND 4.0 for the Data Dictionary and LGPL 3.0 for everything else

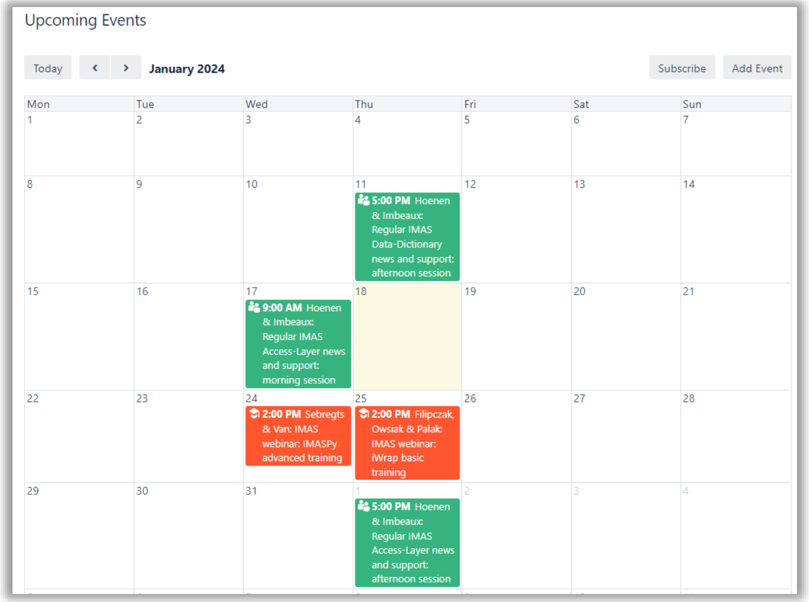
Finally, stay in touch!

- Regular newsletters sent to 700+ recipients
- Regular communication and support meetings
  - Monthly for Data-Dictionary
  - Bi-monthly for Access-Layer
- imasusers.slack.com
  - Open to all (~160 members)





- Recent IMAS events
  - IDS-Validator presentation and training (7 October 2024)
  - Data Dictionary development training (21 May 2024)
  - iWrap basic training (25 January 2024)
  - IMASPy advanced training (24 January 2024)
  - UDA data mapping workshop (20-22 November 2023)
  - Persistent Actor Framework webinar (20 September 2023)
  - MUSCLE3 training (24-27 January 2023)
- Subscribe to our google or confluence calendars →



[Advances in Tokamak Integrated Modelling (22-26 January 2024) · ITER Conference Tool (Indico)]

Thank you for your continued support for ITER!

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