VIRTUAL LAB FOR FUSION

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Abstract

Fusion energy is widely accepted as the energy of the future. However, there is still a lot of work to be done before fusion power plants are able to provide for our cities. One way of speeding the research of fusion technology is the concept of virtual laboratories. In this work we describe a subset of the necessary components of a virtual laboratory, and how they relate to fusion. Once this is established, we present some of the current projects that closely resemble virtual laboratories. We describe them, and then present which components are present and which ones are missing. Finally, with this information laid out we conclude that although many components are indeed present in multiple real life projects, there is still a lot of work to be done before a proper virtual laboratory is established.

1. Introduction

Nuclear fusion has established itself as the energy of the future (Kwon et. al, 2022). After decades of delays, fusion energy is now maturing from a scientific project to an engineering challenge. According to Romanelli et. al. (2020), the first reactor size experimental device - code-named: ITER - is being built in France and experiments are expected to become operational in the latter half of this decade (ITER, 2022). Its plasma (fuel) volume is almost ten (10) times bigger than in the largest fusion experiments in operation today. In general, both physics and technology have sound basis for power production. However, operating machinery such as ITER (or future fusion reactor) requires extrapolation of non-linear and stochastic processes that dominate plasma physics . ITER is expected to prove that a fusion device can produce more energy than it requires (Q=10 target) (ITER, 2022). With its current cost estimate of over 20 billion euros, ITER is one of the most expensive scientific experiments ever (ITER, 2022). At the same time, there are other fusion device geometries and properties that might be more beneficial for fusion energy creation. However, given the cost of the experimental devices, it is difficult to build many of them (Tsuda et. al., 2008). Despite that, several other fusion device projects are ongoing around the world (Kwon et. al, 2022).

In Chapter 2 we divide the fusion process and devices in different parts, each of which have their own challenges regarding simulation and integration. In Chapter 3 we present the state of the art in regards to virtual laboratories, and which of the requirements have been fulfilled. Finally, Chapter 4 concludes the work.

2. Potential requirements for a fusion virtual laboratory

In this chapter we present some of the potential requirements for a fusion virtual laboratory. This is in no way encompassing, and different interpretations might lead to different subsets of requirements - this is an adaptation of the ideas presented by Klami et. al., (2022) .

2.1 Virtual

Naturally, a virtual laboratory needs to be virtual. This allows for users in different locations to access the same laboratory, as well as avoiding physical limitations of current devices. That is, experiments can be executed with parameters currently unattainable by researchers. For example, increasing the device's size. Similarly, experiments can be paused mid execution and later resumed. This is specially interesting given the high computational costs of the modeling of plasma behavior.

2.2 Digital Twins

Digital twins are a desirable technology and many software are available for - but have some limitations - presenting complex physics phenomena and machines. So the effort here is to extend digital twin technologies for fusion research.

2.2.1 Fusion plasma behavior

We currently have multiple methods for plasma simulation. However, high definition methods also incur high computational costs. Approximations have better runtimes, at cost of quality of the results. Each simulation is also limited in the scope of their modeling. For example, specific tools simulate the plasma wall interactions, while others work on modeling the core of the plasma. These different tools need to communicate with each other.

2.2.2 Control of the machine during runtime

Events in a fusion experiment or device are too fast for manual input. Therefore, controllers used need to be pre-designed and automated. This means that creating a compatible version for virtual laboratories should be straightforward, as they are already virtual. These controls include changing the magnetic field to prevent disruptions to the plasma confinement or addition of more fuel/heat to the system.

2.2.3 Virtual diagnostics

Real sensors give raw signals. These are noisy data, which requires a processment before they can be used in further analysis. This pre-process can be for removing noise from the data, or creating a smooth profile of it. A digital twin of such devices then would require to model all these characteristics.

2.3 Integration of Digital Twins

This component refers to the inter digital twin communication. That is, each digital twin must have its input/output related to others. This of course applies only where it is relevant. For example, the different parts of the plasma have different models, and so a core simulation would need to communicate with a plasma wall interaction simulation in order to have a proper modeling of the system as a whole.

2.3.1 Control of the machine during runtime

Running a fusion device requires fast two way communication between the control systems and diagnostics. Therefore, these two digital twins need to be efficiently integrated.

2.3.2 Analysis of experiments

Each experiment produces data that needs to be combined and further modified to be input to different analysis, visualizations, modeling programs, etc. It is important to note that some programs take as input values that are not directly measured, but computed based on other diagnostics. Such values can be ion heating or particle source deposition profiles.

2.3.3 Simulation of experiments

Much of the potential issues for integration of simulations reside on physics related challenges. Each area of the plasma uses its own program for simulation, and each can have not only different timescales but also different spatial dimensions.

2.4 High Performance Computing (HPC)

Current solutions are not able to run full tokamak simulations in high resolution in relevant time scales due to the computational expense. Although simplified models can improve runtime, they lose definition which can be important for describing some plasma behaviors. Not only that, but even reduced models can be computationally expensive for larger scales. This means that HPC is an intrinsic component of fusion simulations, and therefore of virtual laboratories for fusion.

2.5 User Interface (UI)

A user interface is vital for readability of experiments and results. It can also be used for validation of the results, and comparison of simulations to real life experiments.

2.6 Artificial Intelligence (AI)

AI has been implemented in fusion research in the past years (Klami, 2022). The main uses are for surrogate models, disruption predictions and material analysis. Surrogate models attempt to reduce runtime of the computationally expensive models by substituting partially or fully the models with machine learning. Disruption predictions relate to using AI for predicting potential disruptions on the plasma confinement based on the diagnostic data. These disruptions can be financially expensive, as hot plasma can damage the wall or other components of the device once the confinement is lost. Finally, AI can also be used for predicting material characteristics (Klami, 2022). For example, predicting how the energy necessary for dislocations to happen change based on atom vacancies on the material's lattice.

2.7 User access

A virtual laboratory must also provide some way for users to access it. This allows for users from across the world to work together in this digital environment. Naturally, this raises security concerns (Klami, 2022), as only approved users may access the experiment results. More practical concerns relate to the need of high speed connections and real time connections for sensitive experiments, where user input is necessary (Klami, 2022).

This list is in no way encompassing all the possible variables necessary for a proper simulation of a fusion reactor. Even so, a virtual laboratory like this would be extremely challenging and very expensive to build, and no attempt was found in the literature. However, in this study we aim to achieve the following objectives: (1) map what has already been done, (2) identify which pieces (potential components of a virtual laboratory) have already been implemented, and (3) understand what key components (expected to exist in a virtual laboratory) might still be missing from existing implementations (or prototypes) of virtual laboratory for fusion.

3. Literature

In practice, each of the world's experimental fusion devices comes with at least a selection of the components of a virtual laboratory described in this work. This is due to each experimental device being equipped with tens of different and complicated diagnostics, usually requiring data handling post measurement (like any radiation based measurements, such as spectroscopy) and storing of the data somewhere with a controlled access for further use and analysis (Klami, 2022). Since each experimental device is unique, and most of the diagnostics included are unique, the system environments are unique as well. However, there are considerable efforts being made in trying to generalize such environments. For example, data storage, naming standards and analysis codes to be machine independent (Tsuda et al. 2008).

In this chapter we will present some of the examples of fusion projects in the literature, and show which components each of the experiments already implement, and which ones are still lacking.

3.1 Integrated Modelling and Analysis Suite (IMAS)

IMAS is a collection of software that is used for all physics modeling and analysis at ITER (Romanelli et. al., 2020). ITER being the first reactor-size experimental fusion device, which is planned to start experimental operations towards the end of this decade (ITER, 2022). It uses a modular approach and standardized data representation that can describe both experimental and simulation data for any experimental device; this is a necessary step on the way to development of machine-independent codes and workflows and combining the data for extrapolation for ITER. IMAS includes a high fidelity plasma simulator and its components, and data processing and analysis tools.

IMAS is leading data standardization work by assigning standards for data dictionary structures and naming of data, interfaces to data structures, and supported languages (Fortran, C++, Python, Java, MATLAB). Data management is also a challenge because ITER is expected to procure truly big data: about 50 main diagnostics in ITER are expected to generate about 2.2 PB of raw data per day. Most space consuming in this is camera data (ITER, 2022; Romanelli et. al., 2020). Analysis and simulation data generated are not included in the previous figure, but they are not to be nearly that big.

IMAS Plasma simulator is one of the main deliverables: it will be first used for physics validation of plasma scenarios (Romanelli et. al., 2020). There is a risk of breaking the machine if, for example, plasma disrupts too violently so that it melts the first walls and diagnostics there. To try and avoid this there is the need to simulate full pulses from initiation to safe landing, in order to increase confidence that the pulses that are planned to run will not harm the machine. Plasma simulators are also expected to support experimental work: it will be much easier to establish parameter ranges that “might work” or parameter ranges “that will not work” for a desired effect in a working simulator. To have the plasma simulator really working, extensive validation is needed in earlier steps – keeping in mind that data for ITER is extrapolated from current day devices. This is work in progress and will include already existing components like Jintrac (see next chapter).

An integrated approach in data analysis can mean, for example, the use of synthetic diagnostics to evaluate how well they would perform in a real life scenario. At the moment about 20 synthetic diagnostics have been developed or adapted for IMAS (Romanelli et. al., 2020). Work has started to combine signals (e.g. there are two or more plasma density measurements, each with the strengths and weaknesses, so the best result is achieved by combining the measurements info).

3.2 Jintrac and CCFE data infrastructure

JET (Joint European Torus) is Europe’s largest fusion experiment, located in Culham, UK and in operation since 1980s’ (JET, 2022). The current world record of fusion energy (at time of writing) production (59 MJ) was made at JET in 2021.

CCFE (Culhan Center for Fusion Energy) has a very advanced data collection and analysis environment that can be seen as a partial virtual laboratory. Data from different diagnostics used in experiments is processed partly automatically and in almost real time, and partly manually, depending on the diagnostic. The data is standardized, and the JET Data Handbook definition of components is diagnostics, processed data (DDAs), real time systems, and software products.

Jintrac (A System of Codes for Integrated Simulation of Tokamak Scenarios) is a multi-machine capable collection of 25 integrated physics modules with standardized inputs and interfaces (Romanelli et. al., 2014). It was originally developed at the same time with JET construction, and it is written in Fortran. Jintrac is selected as the main component in IMAS flight simulator. Jintrac has integrated core and edge codes and external actors like magnetic confinement, neutral beams and RF heating (radio-frequency). Synthetic diagnostics are not really there, but part of simulations act like them, like PENCIL code that is used to reconstruct deposition profiles of neutral beam injection. Jams, an envelope of software including Jintrac, includes codes that can be used to create and modify experimental data (processed data, DDAs) from JET as inputs to simulations like Jetto or Edge2D. Jetto and other parts can be used with input data from other fusion experiments than JET, but then the user will have to have the input data processed ready already elsewhere. high-performance computing (HPC) with parallelization is available for expensive simulations.

Other fusion experiments have similar set-ups, and partly the codes included in Jintrac are used cross-machines. Turbulent transport simulation codes like TGLF and Qualikiz, which included Jetto in Jintrac, are also included in Astra, which is in use in ASDEX-Upgrade tokamak in Germany.

3.3 Virtual laboratory for fusion research in Japan

Fusion experiments in Japan have been integrated into a virtual laboratory environment (Tsuda et al. 2008). Since experiments and universities have been integrated physically at different locations, emphasis is placed on super-high-speed networks (SuperSINET) (Tsuda et al. 2008). The main emphasis here is to facilitate using large amounts of data accumulated at the fusion experiments' own supercomputers.

A similar system obviously also exists elsewhere, like for JET, but the description of the Japanese set-up is the most detailed and informative that we found online. The main components discussed are remote participation, remote use of the supercomputer system and enabling a country-wide research programme. Here the topic to consider is user access, which is very crucial, as typically the research facilities and the researchers are not located in the same physical location. The aim is to provide access to diagnostic devices and analyze data remotely. It should be noted that it is not just the experiment results that need remote access, but typically also many diagnostic devices are experimental devices on their own, and their running, maintenance and calibration among other things require access by their developers, often employed in various universities and research institutes. According to Tsuda et al the main requirements for the virtual laboratory system are: (1) high-speed access, (2) high-security, (3) easy participation, and (4) good maintenance. While Jintrac is more a physics view to a virtual laboratory, this is more an IT- and access view on the same topic.

3.4 Virtual tokamak platform at KSTAR

KSTAR is a fairly new fusion experiment in Korea. It has been in use since 2008, and it uses superconducting magnets to confine plasma.

In their paper Kwon et al. (2022) they present a very different approach to a virtual tokamak platform. The Unity® game engine is used to visualize the KSTAR machine. This can be run on a personal computer with reduction of CAD data. Three simulations, neutral beam simulation (Monte Carlo code), RF heating simulation (ray tracing code), and 3D magnetic field perturbation simulation, have been integrated into the virtual machine. The aim is integrated visualization of the plasma. Then there is virtualization on top of visualization; there exists an underlying software layer to represent functionalities and process various data associated with visualized objects.

While this solution is very limited in scope, it is very interesting since the visualization approach and the aim for interactive simulations are the main focus. The importance of being able to visualize complicated processes in such a way that they are easier to comprehend cannot be emphasized too much. Jintrac, and IMAS simulation and analysis suite that is based on Jintrac, is more of a typical software, where you give your input, the computer does its thing and gives you the output, and then visualizing this is up to the user in a different software after the simulation. Visualization during runtime is not a consideration. For this the KSTAR solution is a refreshing alternative. However, given the very different time- and length scales that are needed in the simulations, expanding the scope of this concept to cover all the main processes of a tokamak can be very challenging.

3.5 Summary

The examples presented in this chapter partially fit into our definition of virtual laboratories. However, it is important to note that none of them fully accomplishes all the necessary components selected by us. This is shown in the table below.

	Virtual	Digital Twins	Integration	HPC	UI	AI	User access
IMAS	X	X	X	X		X	
Jintrac	X	X	X	X		X	
Kstar	X				X		
Japan	X			X			X

4. Conclusion

Building an actual fusion reactor may well be one of the most complicated tasks humankind has ever attempted. Building virtual laboratories that can combine information from several existing experimental devices in the support of extrapolating results towards bigger future fusion reactors has potential of both speeding up the implementation and saving costs. During our research it became evident that a full-scale virtual laboratory in fusion does not exist yet. Closest thing to one, and the most ambitious, is the IMAS, the integrated modeling and analysis suite that is being built together with the reactor-size experimental device ITER. It aims at standardizing information, thus making it easier accessible for research and analysis.

During our analysis we also concluded that, when building a virtual laboratory, one must also be conscious about what is actually sensible, instead of just following definitions. For example, in fusion experiments several diagnostics are typically used for measuring the same experimental parameter, like plasma density or temperature. Building a digital twin of each one of these might not make sense, since the accuracy of the diagnostics can be tackled separately, and adding tens of digital twins would make the system far more complicated, potentially unnecessarily. On the other hand, having several different software for simulating the phenomenon may be useful from an uncertainty quantification perspective.

We also expect that ML/AI have more to contribute to fusion research than is currently utilized. However, the extrapolation challenge makes understanding of the underlying physics very important, and already for this reason alone it is not likely that ML/AI solutions would fully replace current first-principles based tools. However, emulators / surrogate models have a lot of potential in speeding up routine simulations and Gaussian process regression can be very useful in handling noisy raw data from diagnostics.

References

JET (2022, December 22) JET: the Joint European Torus - Culham Centre for Fusion Energy (ukaea.uk) https://ccfe.ukaea.uk/research/joint-european-torus/

Klami, A., Damoulas, T., Engkvist, O., Rinke, P., & Kaski, S. (2022). Virtual Laboratories: Transforming research with AI.

Kwon, J. M., Choi, H., Ki, J., Park, S. Y., Park, S. H., Kim, Y. J., ... & Han, H. (2022). Development of a Virtual Tokamak platform. *Fusion Engineering and Design*, *184*, 113281.

Romanelli, M., Coelho, R., Coster, D., Ferreira, J., Fleury, L., Henderson, S., ... & WPCD Team. (2020). Code integration, data verification, and models validation using the ITER integrated modeling and analysis system (IMAS) in EUROfusion. *Fusion Science and Technology*, *76*(8), 894-900.

Romanelli, M., Corrigan, G., Parail, V., Wiesen, S., Ambrosino, R., Belo, P. D. S. A., ... & EFDA-JET, C. (2014). JINTRAC: a system of codes for integrated simulation of tokamak scenarios. *Plasma and Fusion research*, *9*, 3403023-3403023.
ITER. (2022, December 22). *Fusion Energy*. Retrieved from https://www.iter.org/

Tsuda, K., Nagayama, Y., Yamamoto, T., Horiuchi, R., Ishiguro, S., & Takami, S. (2008). Virtual laboratory for fusion research in Japan. *Fusion engineering and design*, *83*(2-3), 471-475.

Reading

(YouTube video clip - 6 mins) Inside an experimental fusion energy laboratory

https://www.youtube.com/watch?v=dSa95AoFFz8