Digital Solution for fusion Department towards Digital Twin

(some idea from E-TASC GM, https://indico.euro-fusion.org/event/3034/)

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Terminology convention

What is the "digital twin"?

*Grieves and Vickers definition : https://rdcu.be/d1wRu

Digital Twin (DT) - is a set of virtual information constructs that fully describes a potential or actual physical object from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin.

Digital Twin Prototype (DTP) - contains the informational sets necessary to describe and produce a physical object duplicating virtual version. These informational sets include, but are not limited to, Requirements, Fully annotated 3D model, Bill of Materials (with material specifications), Bill of Processes, Bill of Services, and Bill of Disposal.

Digital Twin Instance (DTI) - describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product.

Digital Twin Environment (DTE) - this is an integrated, multi-domain physics application space for operating on Digital Twins for a variety of purposes. These purposes would include:

- Predictive - would be used for predicting future behaviour and performance of the physical product; and
- Interrogative - this would apply to DTI's being interrogated for the current achievements

Applied to EUROfusion objectives

A Digital Twin for fusion is a virtual model of a fusion reactor that simulates and monitors its real-world counterpart. It uses real-time data from sensors and other sources to replicate the reactor's physical structure, plasma behaviour, material interactions, and engineering systems. The goal is to improve predictions, optimize performance, reduce risks, enhance efficiency, and support decision-making by creating a comprehensive, real-time, and actionable representation of a system.

DTE/I – is not only code(s)! Includes any digitalised information that can be used for prediction (of future machines, e.g. ITER, DEMO) or analysis (of currently running e.g. MST, W7X)

Key features expected from DTE/I:

- **Simulation and Modelling**: Use of developed codes and models to simulate behaviours, predict outcomes, and test scenarios (mostly TSVV/ACH outcome);
- **Data Analytics**: Existing experimental and simulation data analysed with AI, machine learning, or other advanced techniques to identify patterns and improve predictability (AI/ML projects, DMP);
- **Real-time Integration**: Improve machine operation by broader use of multi-fidelity simulators (HFPS, PDT, Flight Simulator);
- **Feedback Loops**: Optimisation of scenarios, control loops and machine design (Integration with Eng. codes).

Key applications of DTE/I for fusion

Physics

Diagnostic and Systems

Engineering

1. Scenario Testing and Training:
- Test operational scenarios (e.g., plasma heating, fuelling, magnetic field configurations) in the virtual environment to identify optimal setups.
- Train operators and researchers using the digital twin without risking the physical device.

2. Cross-Tokamak Comparisons:
- Compare performance and scenario transferability using shared digital twins for different tokamaks (e.g., MST, JET, ITER, DEMO).

3. Plasma Physics and Control:
- Simulate plasma behaviour in real-time, including dynamics, instabilities, disruptions, and runaway electrons.
- Optimize plasma control strategies by running "what-if" scenarios without interfering with actual operations.
- Improve predictions of plasma confinement and performance under different operational conditions.

4. Disruption Mitigation:
- Simulate disruptions and their mitigation strategies, including the injection of impurities or magnetic coil responses.
- Use real-time data to predict disruptions before they occur and take corrective actions.

5. Material and Component Analysis:
- Study how plasma-material interactions (e.g., erosion, deposition, and radiation effects) impact tokamak components like divertors or first walls.
- Model and evaluate advanced materials and configurations for improved durability and performance.

6. Diagnostics Integration and Validation:
- Validate and cross-check data from diagnostics by comparing real measurements with the digital twin model's output.
- Enhance data analysis and interpretation by integrating multi-physics and multi-scale models.

7. Engineering Design and System Integration:
- Simulate and optimize tokamak subsystems such as cooling systems, power supply networks, or control actuators.
- Accelerate the design of next-generation tokamaks (like DEMO) by iterating designs virtually.

8. Fusion Reactor Design and Scale-up:
- Enable integrated simulations for fusion power plants by combining plasma physics, materials science, and engineering systems.
- Optimize reactor designs for scalability and efficiency, leveraging insights gained from current tokamaks.

9. Predictive Maintenance and Optimization:
- Monitor tokamak components (like superconducting magnets, vacuum vessel, or divertor) for wear, tear, or damage.
- Predict component failures or degradation and optimize maintenance schedules to minimize downtime.
- Evaluate and test the impact of hardware changes on overall tokamak performance.

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What do we need to have DTE/I

Data Infrastructure: all kind high-quality data, (plasma, materials, machine components and actuators); standardised data formats and interfaces; FAIR data management; uncertainty quantification)

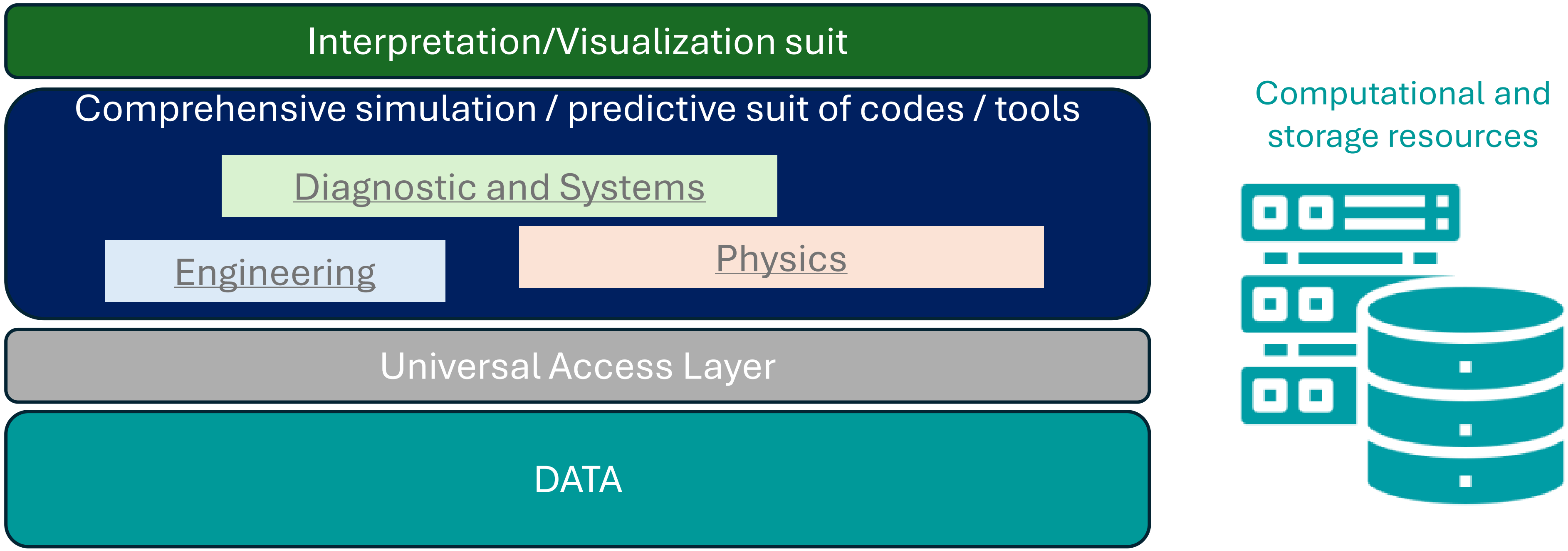
Predictive and Simulation Codes: Physics-Based models; AI/ML models; HPC Compatibility; frameworks to couple multiple simulation domains

Real-Time Feedback Systems: control algorithms; integration with real tokamak

Visualization Tools: friendly UIs, 3D visualisation, tools for evaluation of DTE predictions vs experiment

Benchmarking and Validation: accuracy and reliability of DTE

Computing and storage resources



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How do we see the situation in 2024?

Many of the required elements for progressing towards DTE are already present within the DSD work programme:

1. **Enormous Volume of Experimental/Modelling Data**
2. **Code Development through TSVVs**
   Advanced plasma physics and material codes are being developed, enhanced and in the release process to the community
3. **Professional Support by ACHs**
   - High-performance computing (HPC) adaptation
   - Advanced visualization tools
   - IMAS interfaces to ensure seamless integration
4. **Pilot AI/ML Projects**
   Exploratory projects applying AI/ML techniques to address specific objectives of WPs
5. **Established Data Management Plan (DMP)**
   - Guarantee for compliance with FAIR principles
   - Provision of tools ensuring efficient data access
6. **Dedicated HPC and Gateway resources**

Backup

Actions towards DTE

To continue towards a fully integrated DTE some shaping and gaps coverage is required

E-TASC Activities

TSVV projects to focus on

- Supporting both plasma physics and engineering needs
- Validation and Applications: Enhancing coordination with Work Packages
- Code Deployment: Advancing user training and support

Strengthen **ACH** contributions, including

- adaptation of tools to HPC systems
- advanced visualization
- Implementation of standardised IM platform (IMAS, DevOps, ...)

Expand **AI/ML projects** under E-TASC to address specific DTE gaps

Addressing Physics Gaps

- Core transport and edge physics for ITER and DEMO
- Disruptions and runaway electrons
- Plasma exhaust and divertor solutions
- Predictive capabilities (including VVUQ) and reduced models for "flight simulators“

Expansion into fusion engineering and materials research

Secure additional resources such as LTDSF (Long-Term Data Storage Facility) for robust data management

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Particular gaps / actions

Gaps / Missing Elements	Means to Cover	Mechanism
Lack of physics understanding in some areas	Long term: Develop advanced theories and models.	Multi-year focused projects for theory development (TSVV-like framework).
	Short term: Apply AI/ML techniques to address immediate gaps.	Preferential support for targeted AI/ML-based models.
Integration with engineering codes	Involve DEMO department(s) to integrate their codes into an established platform.	Pilot interdisciplinary projects involving plasma physics and engineering expertise (BB?).
	Standardize data sharing, code development, and integration formats across domains.	Develop translation tools to support integration (ACH?).
LTDSF (Large-Scale Test Data Storage Facility)	Develop a new facility to support DTE infrastructure.	Procurement process for new facility development.
Friendly User Interfaces (UIs)	Design and develop new user-friendly interfaces.	Assign as a new development task within ACH.
Tools for evaluation of DTE predictions vs. experiments	Define and implement tools to compare and evaluate DTE outputs against experimental results.	Mechanism to be defined based on identified project needs.
Benchmarking and validation	Collaborate with PSD on benchmarking activities.	Launch pilot projects focused on leveraging TSVV codes for validation.
DMP (Data Management Plan) completion	Extend the DMP to include scenarios C and D.	Extend DMP activities as part of the 2026–27 program.
UQ (Uncertainty Quantification)	Introduce tools and methods for uncertainty quantification.	Align UQ efforts with adjustments to the 2026–27 TSVV program.