EUROfusion

A highly scalable and flexible digital twin of fusion power plants

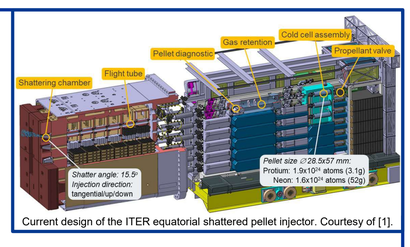
C. Sommariva[1], F. Cabot[2], D. Fransos[3], S. Kerboua-Benlarbi[1], C. Angerer[3], C. Favreau[3], F. Yang[3], H. Elaian[1], M. Toussaint[1], A. Fedrigucci[1,4], A. Pau[1], P. Blachard[1], S. Duthaler[3], H. Reimerdes[1], O. Sauter[1], E. Tonello[1], C. Yildiz[1] and J. Zielinski[3]

[1]École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland
[2]École Polytechnique Fédérale de Lausanne (EPFL), Scientific IT & Application Support (SCITAS), CH-1015, Switzerland
[3]NVIDIA Corporation, 2788 San Tomas Expressway, Santa Clara, California, 95051, USA
[4]École Polytechnique Fédérale de Lausanne (EPFL), Theory and Simulation of Materials (THEOS), and National Centre for Computational Design and Discovery of Novel Materials (MARVEL), CH-1015, Lausanne, Switzerland

Introduction

Physics-based design of high-performance fusion devices & components may be an overwhelming tasks:

- Complex, coupled multi-physics problems to be solved
- Thousands of sub-systems must be designed and interfaced
- Nevertheless, optimal functionality & longevity must be granted!
  - ⇒ Design time & costs exponentially increase w design complexity
  - ⇒ **Need to streamline and integrate the design workflow for cutting down both R&D costs and time-to-product!**

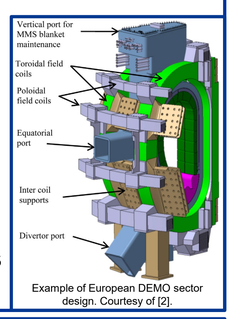


Current design of the ITER equatorial shattered pellet injector. Courtesy of [1].

Fusion Digital Twin (FDT) project

Objective: provide an integrated physics & engineering framework for the design, simulation and optimization of fusion devices

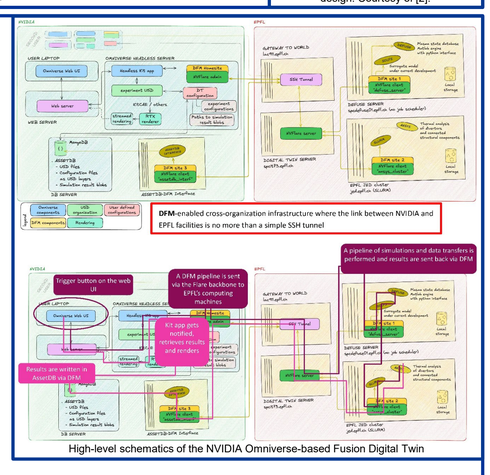
- ⇒ Micro-service infrastructure based on the NVIDIA Omniverse ecosystem
- ⇒ Integrates simulators, surrogate models, renderer & database handling frameworks
- ⇒ "in-the-cloud": pipeline execution distributed on multiple computational resources



Example of European DEMO sector design. Courtesy of [2].

Fusion Digital Twin architecture

- **NVIDIA Data Federation Mesh** (DFM) [3]: connects, manages and orchestrates the execution of simulation pipelines and data transfer between services and computation resources
- ⇒ **micro-service architecture**: applications are represented as services in FDT and connected to DFM via adapters
  - ⇒ Arbitrary large number of services can be connected
  - ⇒ Currently connected services: DEFUSE, MatLab, Ansys, SLURM, SOLPS Surrogate, Carbon Sputtering (to do)
- ⇒ **in-cloud execution**: services can be distributed and executed on different computational resources or "sites"
  - ⇒ Prevents transfer of heavy and/or confidential data performing heavy computations on the data site
  - ⇒ Current FDT sites: NVIDIA, SCITAS & SPC clusters
  - ⇒ Orchestration and data transfer between sites performed "under-the-hood" by NVIDIA DFM
- ⇒ **Programmable pipelines**: pipelines fully programmable via Pythonic domain specific language

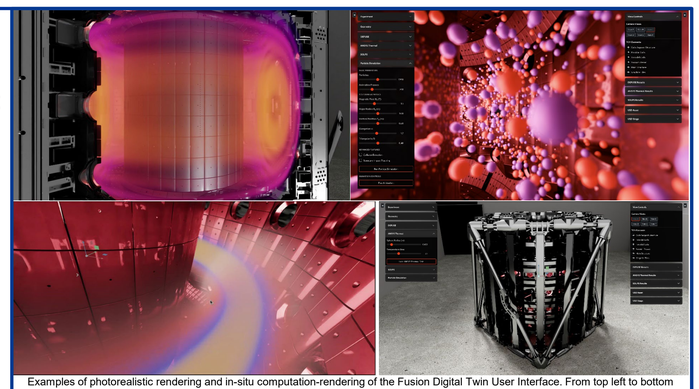


High-level schematics of the NVIDIA Omniverse-based Fusion Digital Twin

Photorealistic graphical interface

FDT User Interface (UI) based on **NVIDIA Kit-App** and **RTX rendering** [4] technologies:

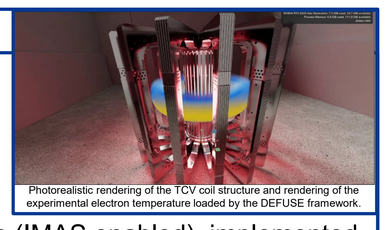
- Photorealistic rendering from device CAD:
  - Inner wall, vacuum vessel, toroidal & poloidal field coils, metallic structures.
- Successful rendering of experimental data
- Successful rendering of simulation data
- Successful in-situ (in-GPU) simulation and rendering of plasma properties
  - Plasma particle simulations using TCV magnetic field and Boris particle pusher
  - Dynamic simulation & rendering of coil magnetic field via Biot-Savart law
- User-friendly web-based user interface for setting pipeline inputs and rendering of simulation results
  - UI accessible via web-browser (no local installation needed by the user)


Examples of photorealistic rendering and in-situ computation-rendering of the Fusion Digital Twin User Interface. From top left to bottom right: in-situ computation – rendering of coil magnetic field, in-situ computation – rendering of plasma electron and ion dynamics, photorealistic rendering of TCV CAD and experimental electron temperature and photorealistic rendering of TCV structure from CAD.

Fusion Digital Twin services

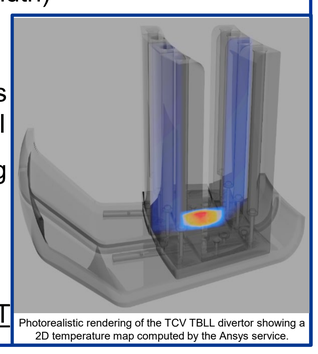
DEFUSE & MatLab services (executed within the EPFL-SPC site)

- **DEFUSE** [5]: framework developed at EPFL-SPC for handling of experimental fusion plasma databases and the analysis of their data.
  - Database framework widely used in the fusion community: TCV, JET, ASDEX-Upgrade, MAST, WEST, JT60SA, ITER, DIIID, …
  - Service for reading/writing data from/to version-controlled databases (IMAS enabled) implemented
    - Support for MatLab and Python interfaces available, Python reading routine connected to FDT
- **MatLab** [6]: programming and numeric computing platform for engineering and scientific applications.
  - MatLab service for setting data to and getting data from an active MatLab session implemented
  - Methods for executing arbitrary commands on an active MatLab session implemented in the service
  - MatLab started as a shared headless session (one session handles multiple independent pipelines)
  - Adapters for connecting the MatLab service to FDT under development.


Photorealistic rendering of the TCV coil structure and rendering of the experimental electron temperature loaded by the DEFUSE framework.

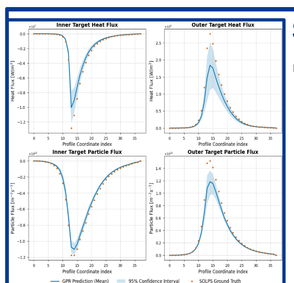
Ansys & SLURM services (executed within the EPFL-SCITAS site)

- **Ansys** [7]: ecosystem of software widely used for the design, simulation and analysis of complex engineering systems (e.g. thermomechanical optimization of components)
  - Generated 2D Ansys models for TCV unbaffled, Short-Inner Long-Outer (SILO) and Tightly Baffled Long Legged (TBLL) divertor (TBLL model parametrized w.r.t. the baffle width)
    - TBLL model parametrized w.r.t. the baffle width
  - Developed services for the Ansys Design Modeler & Ansys Mechanical
    - Ansys compatible mesh generation produced by Ansys Design Models
    - Thermal calculation from components performed by Ansys Mechanical
- **SLURM** [8]: utility for computational resource management and job scheduling
  - Workload manager adopted worldwide and by the european clusters
  - Developed SLURM service for: prepare, submit, verify the status and retrieve results of computational jobs
- Ansys and SLURM services & adapters fully developed and integrated in FDT

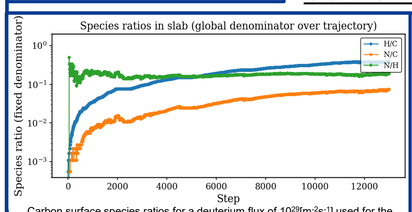

Photorealistic rendering of the TCV TBLL divertor showing a 2D temperature map computed by the Ansys service.

SOLPS-ITER Fast Inference (SOLFS, executed within the EPFL-SPC site)

- Surrogate model of SOLPS-ITER for inference of plasma heat & particle fluxes
  - Architecture: Principal Component Decomposition and Gaussian Process Regressor trained on **112** SOLPS-ITER TCV simulations
  - Input parameters: divertor configuration, plasma core power, deuterium fueling flux, nitrogen seeding flux and divertor baffle width
  - Adequate for FDT Proof-of-Concept purposes but:
  - ⇒ over/under-shoots of the SOLPS-ITER results for peaked values
  - ⇒ Large variance of the mean heat & particle fluxes
    - ⇒ **Large training database required for improving performances**
- SOLFS integrated and connected to FDT via the SOLPS Surrogate service



Particle and heat flux inferences of SOLPS-ITER Surrogate for TVC SILO baffled divertor for a plasma core power of 1300[kW]. Blue lines are the mean inference values, red dots are actual SOLPS-ITER solutions, and the blue faded areas represent the inference confidence level at 95%.



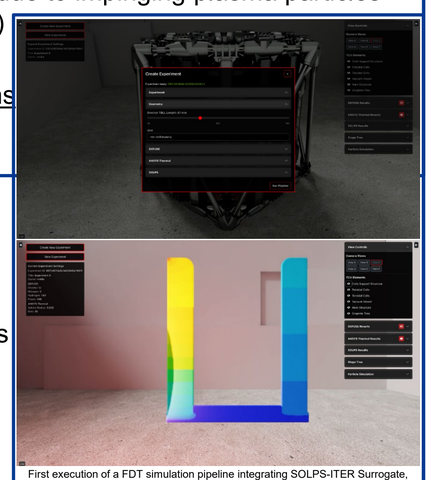
Carbon surface species ratios for a deuterium flux of 10^{29}[m^{-2}s^{-1}] used for the validation of the carbon sputtering Molecular Dynamics simulation framework.

Carbon sputtering (CS) service

- Surrogate model for fast inference of carbon atoms & molecules sputtered from the carbon walls due to impinging plasma particles and impurities (nitrogen seeding)
- Database under construction
  - ⇒ molecular dynamics simulations verified against previous work
- Surrogate model to be developed and integrated in FDT soon!

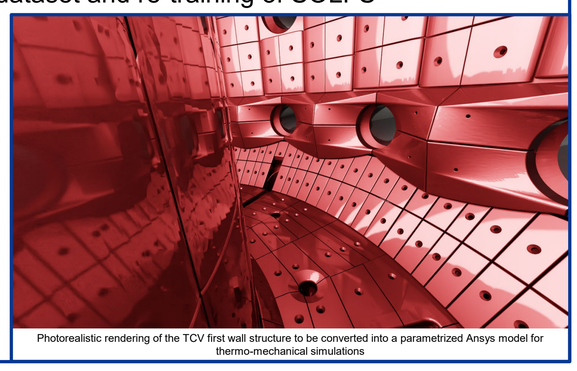
Final result: integrated simulation physics – engineering simulation of TCV Tightly Baffled Long Legged divertor

- Input parameters set in the FDT UI running on the NVIDIA site
  - Photorealist rendering of TCV displayed in UI
- DFM transfer the inputs to the EPFL – SPC and EPFL-SCITAS sites
- SOLPS Surrogate (SOLFS) predicts the heat and particle fluxes impinging on the 2D model of the TCV TBLL divertor
  - Fluxes are transferred to the EPFL-SCITS site
- Ansys mesh and thermal simulation of TBLL divertor performed on the EPFL – SCITAS site
- Results are returned and displayed by the FDT UI at the NVIDIA site


First execution of a FDT simulation pipeline integrating SOLPS-ITER Surrogate, Ansys thermal simulation, parametric 2D TCV divertor model, photorealistic rendering user interface. Top image shows the FDT experiment input window with 3D photorealistic rendering of TCV. The bottom plot shows the 2D temperature map of the TCV divertor. Simulation parameters are: TCV TBLL Divertor w baffle width of 87[mm], plasma core power: 400[kW], deuterium fueling: 1.62[10^{20}s^{-1}] and no nitrogen seeding.

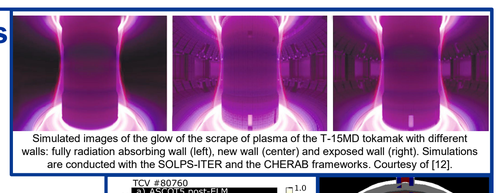
What's next? Extension of the current Fusion Digital Twin services

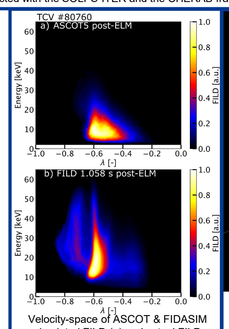
- Extension of the Ansys services towards complex multi-physics 3D simulations
  - ⇒ Generation of parametrized 3D thermo-mechanical model of TCV first wall
  - ⇒ Extension of Ansys Mechanical for supporting 3D thermo-mechanical simulations
- Full integration of the DEFUSE service for generating and manipulation of version-controlled IMAS-compatible databases of the FDT simulation results
- Improvement and extension of the SOLPS-ITER Surrogate model (SOLFS)
  - ⇒ Generation of extended SOLPS-ITER simulation dataset and re-training of SOLFS
  - ⇒ Extension to the Inferences of radiation sources
- Fully integrate the MatLab service in FDT
- Development and integration of Carbon Sputtering
  - ⇒ Finalize Molecular Dynamics simulation database
  - ⇒ Train and integrate in FDT CS surrogate model
- Extend the User Interface rendering capabilities
  - ⇒ Add multiple device subsystems in the renderer
  - ⇒ Deploy in-situ simulation & rendering models
- Development of FDT infrastructure for long-term maintenance & deployment on EUROfusion Gateway


Photorealistic rendering of the TCV first wall structure to be converted into a parametrized Ansys model for thermo-mechanical simulations

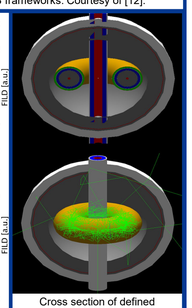
What's next? New physical simulation capabilities

- Development and integration of a physic-based ray-tracing service most likely based on the CHERAB package [9]
  - ⇒ Enable simulation of radiative heat flux deposition of the fusion device first wall (2D radiative sources only)
  - ⇒ Enable the development of synthetic diagnostics
- Development of a service integrating the ASCOT code [10] in FDT
  - ⇒ ASCOT is the leading particle tracking code for simulating fast ion and electron dynamics in complex plasma configurations
  - ⇒ Simulation of neutral beam, radio-frequency and fusion heating
  - ⇒ Simulation of wall heating from fast particle losses
- Integration of the GEANT4 particle-matter interaction toolkit [11]
  - ⇒ GEANT4 is the leading toolkit of CERN for simulating the physics of energetic particle – matter interactions
  - ⇒ Volumetric energy deposition of fast ions & electron colliding with the first wall plasma facing components
  - ⇒ Development of synthetic diagnostics such as HXR, SXR, gamma and neutron spectrometers
  - ⇒ Possible extension to neutronic simulation of the device (NBI and fusion generated neutrons)
- **Implementation of pipeline for the comprehensive simulation of the plasma wall heating and its 3D thermomechanical response together with photorealistic rendering of the solutions**


Simulated images of the glow of the scrape of plasma of the T-15MD tokamak with different walls: fully radiation absorbing wall (left), new wall (center) and exposed wall (right). Simulations are conducted with the SOLPS-ITER and the CHERAB frameworks. Courtesy of [12].



Velocity-space of ASCOT & FIDASIM simulated FILD (a) and actual FILD measurement (b) of post-ELM fast & slowed-down ion losses in TCV. Courtesy of [13].


Cross section of defined tokamak machine parts in GEANT4. Courtesy of [14].

Conclusions & outlook

- The successful Fusion Digital Twin Proof-of-Concept project shows the possibility of performing integrate physics-engineering simulations of fusion device components distributed on multiple computational resources, with photorealistic rendering of the results and an intuitive user interface
- The current project will evolve the Fusion Digital Twin Proof-of-Concept towards a fully integrated platform for the simulation, optimization and validation of the first wall design of fusion systems

EPFL Swiss Plasma Center
EPFL SCITAS Scientific IT and Application Support
NVIDIA

[1] S. Jachmich et al., "ITER disruption mitigation system design and application strategy", 30th IAEA Fusion Energy Conference, 13-18 October 2025, Chengdu, People's Republic of China
[2] O. Crofts et al., Fus. Eng. Design, vol.109, p.1392, 2016
[3] https://github.com/NVIDIA-Omniverse-blueprints/earth2-weather-analytics/blob/main/docs/05_data_federation_mesh.md
[4] https://github.com/NVIDIA-Omniverse/kit-app-template
[5] A. Pau et al., A Modern Framework to support disruption studies: the EUROfusion disruption database, Proc. Of the 29th Fusion Energy Conference (IAEA-FEC), 16-21 October 2023, London, UK
[6] www.mathworks.com
[7] www.ansys.com/
[8] www.slurm.schedmd.com
[9] C. Giroud et al., Cherab Spectroscopy Modelling Framework (Version 0.1.0), 2018, March 03, Zenodo. http ://doi.org/10.5281/zenodo.1206142
[10] E. Hirvijoki et al., Comp. Phys. Comm., vol. 185, p. 1310, 2014
[11] J. Allison et al. Nucl. Inst. Meth Phys. Res. Sec. A: Acc., Spec., Detect. & Ass. Equ., vol.835, p.186, 2016
[12] V.S. Neverov et al., Phys. of Atom. Nuclei, vol.86, pp.S159, 2023
[13] J. Poley-Sanjuán et al., Nucl. Fusion, vol.65, p.092006, 2025
[14] M. Mehdi Nasseri, J. Fusion Energ., vol.35, p.621, 2016
[15] S. Dasbach, S. Wiesen, Nucl. Mat. Energy, vol. 34, p. 101396, 2023
[16] S. Wiesen et al., Nucl. Fusion, vol. 64, p. 086046, 2024
[17] S. Wiesen et al., J. Nucl. Mat., vo.463, p.480, 2015
[18] X. Bonnin et al., Plasma and Fusion Research, vol.11, p.1403102, 2016

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.