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4th Annual Meeting of EUROfusion HPC ACHs

The Fusion Digital Twin: Integrating Databases, Simulation, AI Surrogates and Visualization for Design Workflows of Fusion Devices

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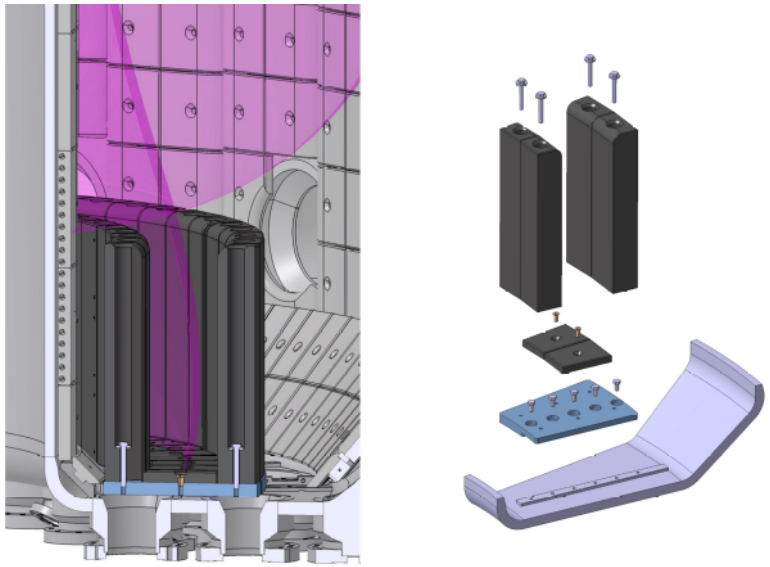
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OUTLINE

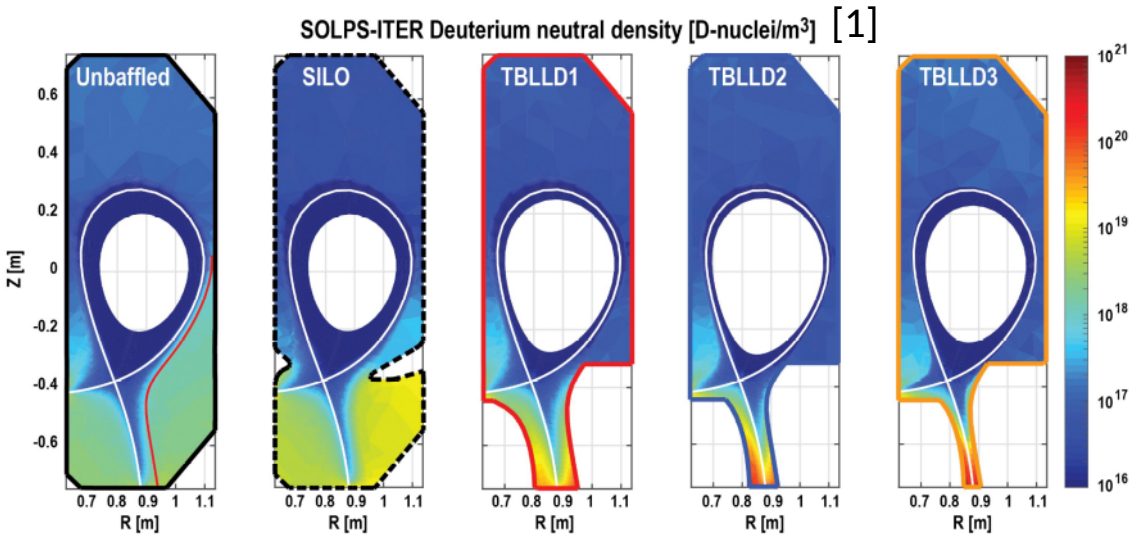
- Introduction
  - Context (TBLLD)
  - Digital Twin motivation
- Fusion Digital Twin
  - Main use case
  - Technologies (Scientific Tools & NVIDIA Tools)
  - Architecture
  - Results
- Conclusion / Future Work


INTRODUCTION

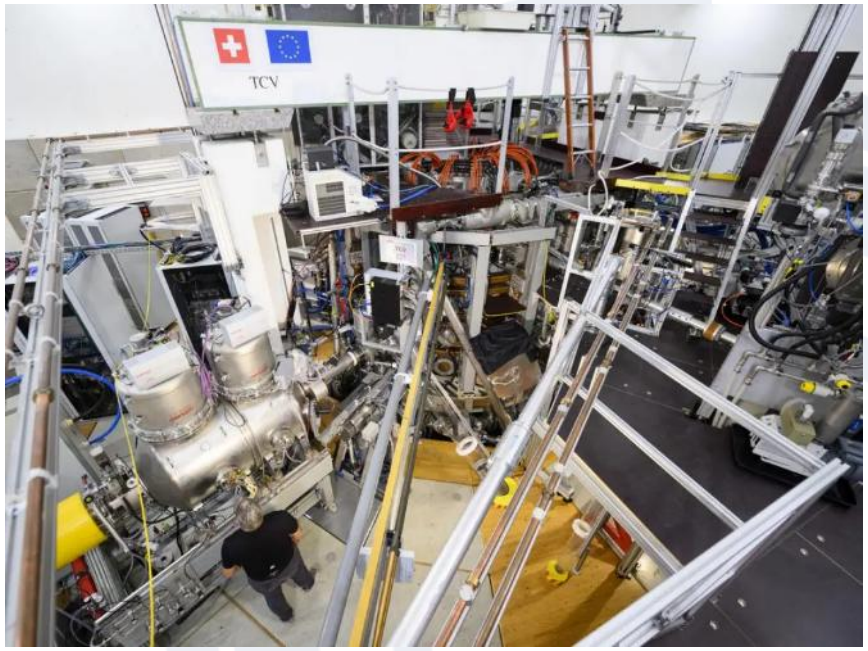
INTRODUCTION: TCV TBLLD



Tightly Baffled Long-Legged Divertor [1]



[1]



EPFL Swiss Plasma Center Tokamak
TCV (Tokamak à Configuration Variable)

- Experimental Campaigns in TCV to study advanced divertor configurations underway
- The Tightly Baffled Long-Legged Divertor (TBLLD) configuration will be next
- TBLLD objectives: better heat dissipation properties and confine the seeded gas away from the plasma core

[1] Reimerdes, Holger, et al. "Implementation of a Tightly-Baffled, Long-Legged Divertor (TBLLD) in TCV." 30th IAEA Fusion Energy Conference (FEC 2025). 2025.

INTRODUCTION: DIGITAL TWIN MOTIVATIONS

- Fusion power plants: complex systems with millions of integrated components!
- All components & integration must be optimized for powerplant performance
- Time & resource intensive process: many iterations between multiple physics, engineering & technical teams

→ Automation of the design & optimization workflows in a single virtual environment

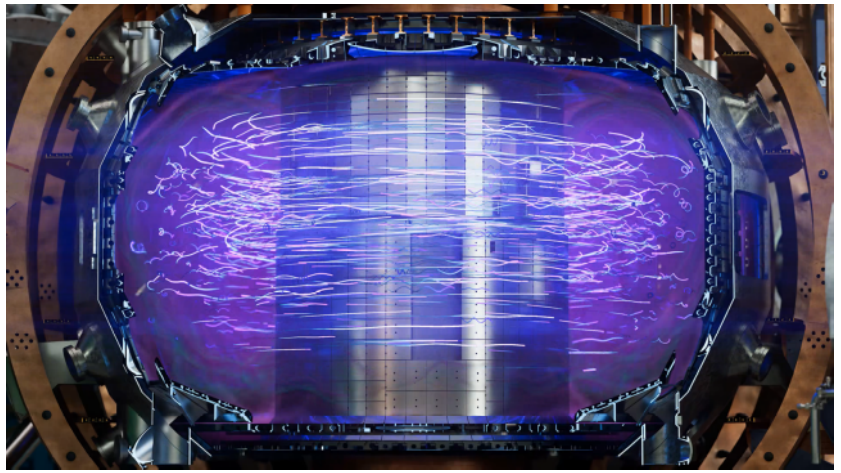
= Digital Twin

Expected cuts in resources consumption and time-to-solution!

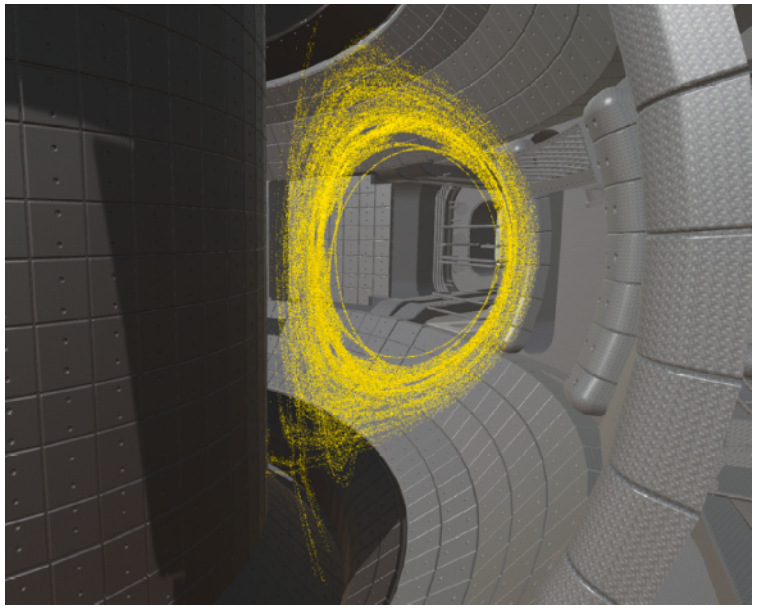
Additional benefits of a fusion digital twin:

- integrated design and analysis of fusion scenarios and control systems
- fast analysis, visualization and simulation of fusion experimental data (Digital Twin-enabled Control Room)
- training of maintenance robots control system in a virtual environment
- training of fusion device operators in a virtual environment
- enabling and improving outreach activities

INTRODUCTION: DIGITAL TWINS FOR FUSION DEVICES



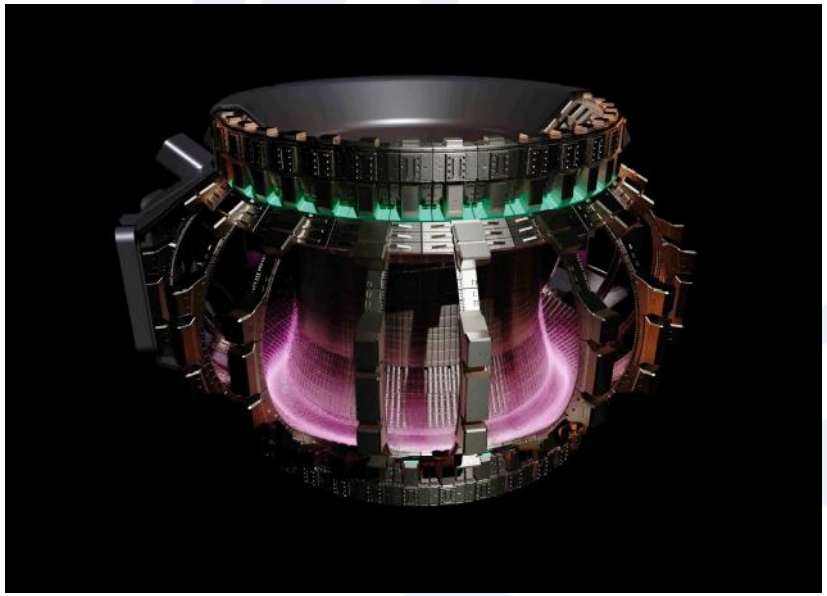
DIII-D Digital Twin [2]



KSTAR Digital Twin [3]

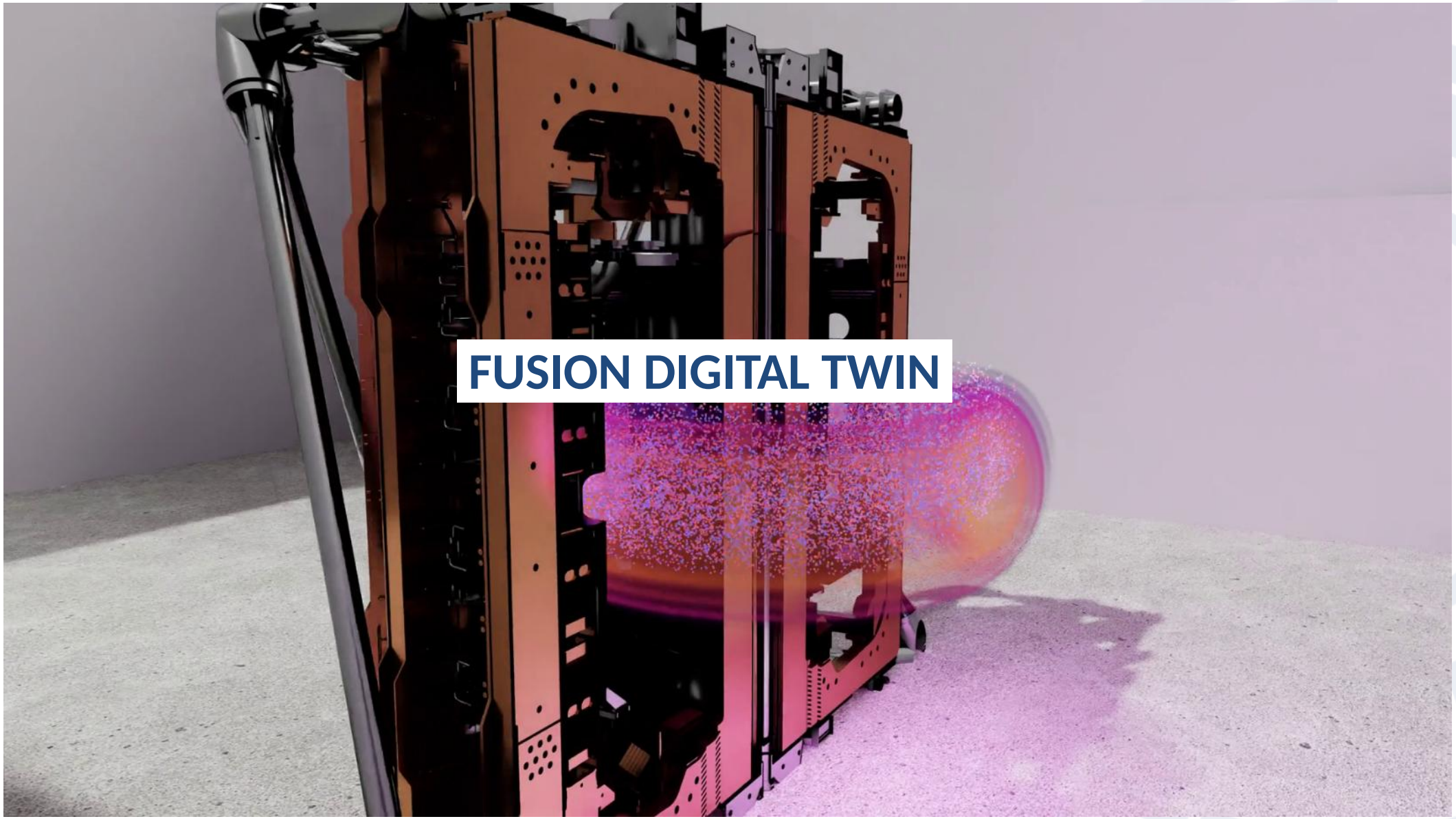
Digital Twin:
- Dynamic virtual representation of a complex real-world system
- Combines numerical simulation, real-world data, AI surrogate models and visualization tools to analyze and test scenarios independently of the physical system

Examples of Digital Twins for tokamaks outside of EUROfusion:
- DIII-D, General Atomics in San Diego, USA
- KSTAR, Korea Institute of Fusion Energy in Daejeon, South Korea
- SPARC, Commonwhealth Fusion Systems in Devens, USA



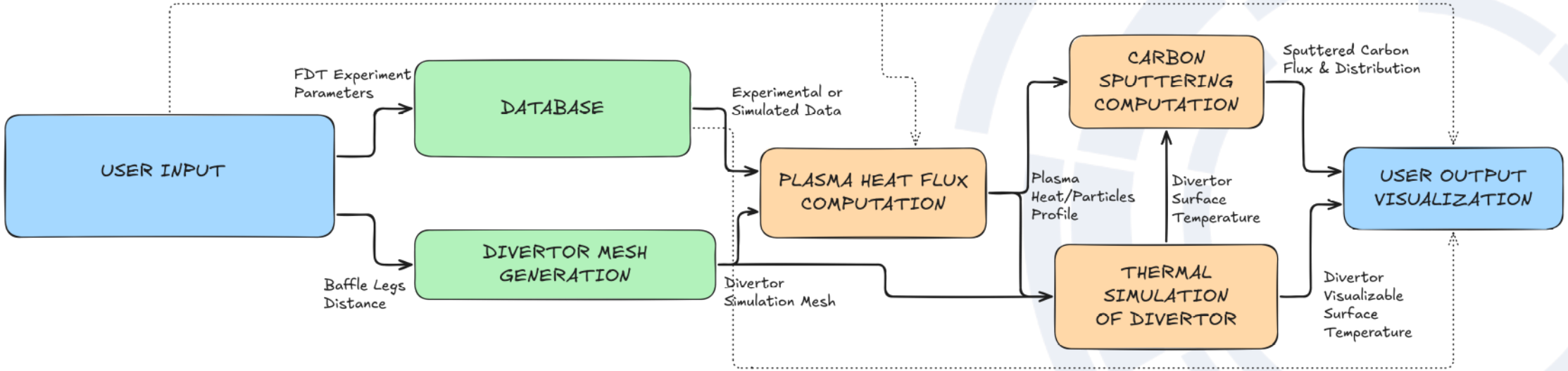
SPARC Digital Twin [4]

[2] https://blogs.nvidia.com/blog/nvidia-general-atomics-fusion/
[3] Kwon, J. M., Choi, H., Ki, J. et al. (2022). Development of a virtual tokamak platform. Fusion Engineering and Design, 184, 113281.
[4] https://blog.cfs.energy/how-nvidia-ai-and-simulation-libraries-and-siemens-tools-can-accelerate-fusion-energy/


FUSION DIGITAL TWIN

FUSION DIGITAL TWIN: INITIAL USE CASE

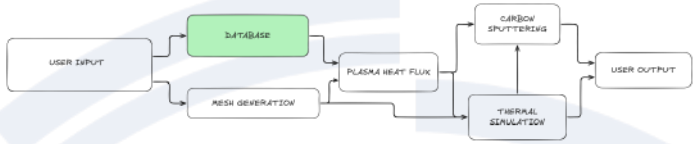
We want to focus on a simple use case to kickstart the Digital Twin and start integrating multiple codes. We want to assist in optimizing the design of the TBLLD using this **high-level** workflow:

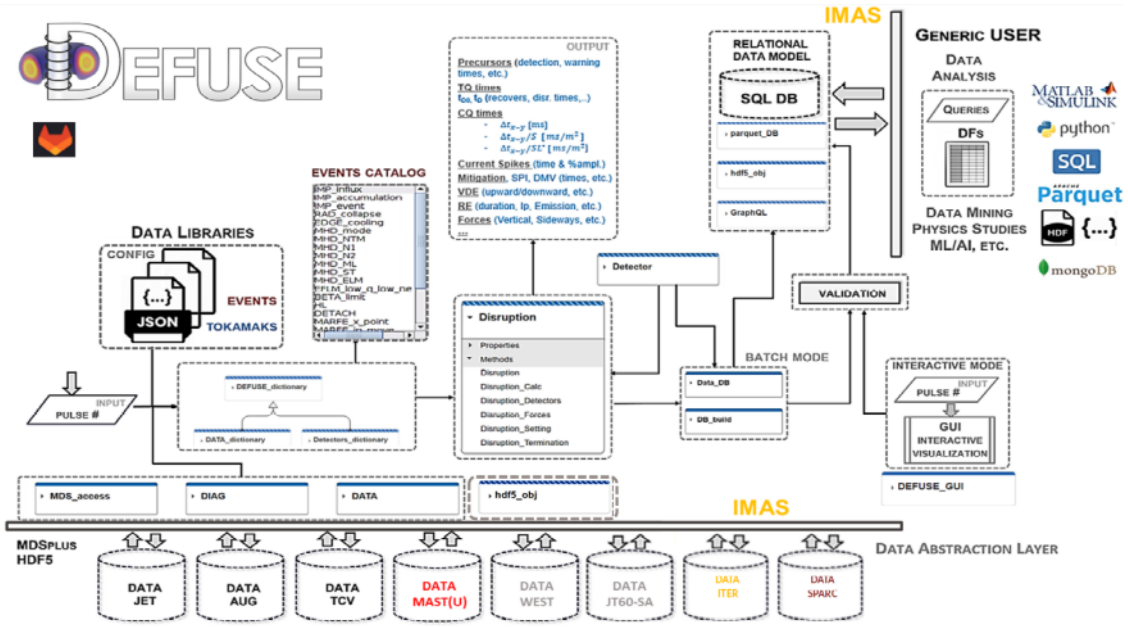


Limitations of the model:

- No analysis of the effect of carbon sputtering on the plasma yet (cooling/pollution)
- 2D analysis of all divertor configurations
- Restricted to thermal analysis (neither mecanical nor electromagnetic simulation)

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING





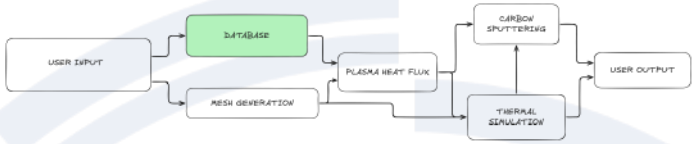
DEFUSE architecture [5]

DEFUSE service

- Allows the usage of the Disruption and Event analysis framework for FUSion Experiments within the FDT
- DEFUSE implements an interface layer to access the data from different fusion experiments, compatible with most of the fusion databases (TCV, JET, ASDEX, WEST, …)
- The FDT service interfaces with DEFUSE to retrieve the experimental data required to run a simulation pipeline
- It stores the query results in version-controlled IMAS-compatible HDF5 files that can be reused in future workflows (simulation, visualization, …)

[5] Pau, Alessandro, et al. "A Modern Framework to Support Disruption Studies: The Eurofusion Disruption Database." 29th IAEA Fusion Energy Conference (FEC 2023). 2023.

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING

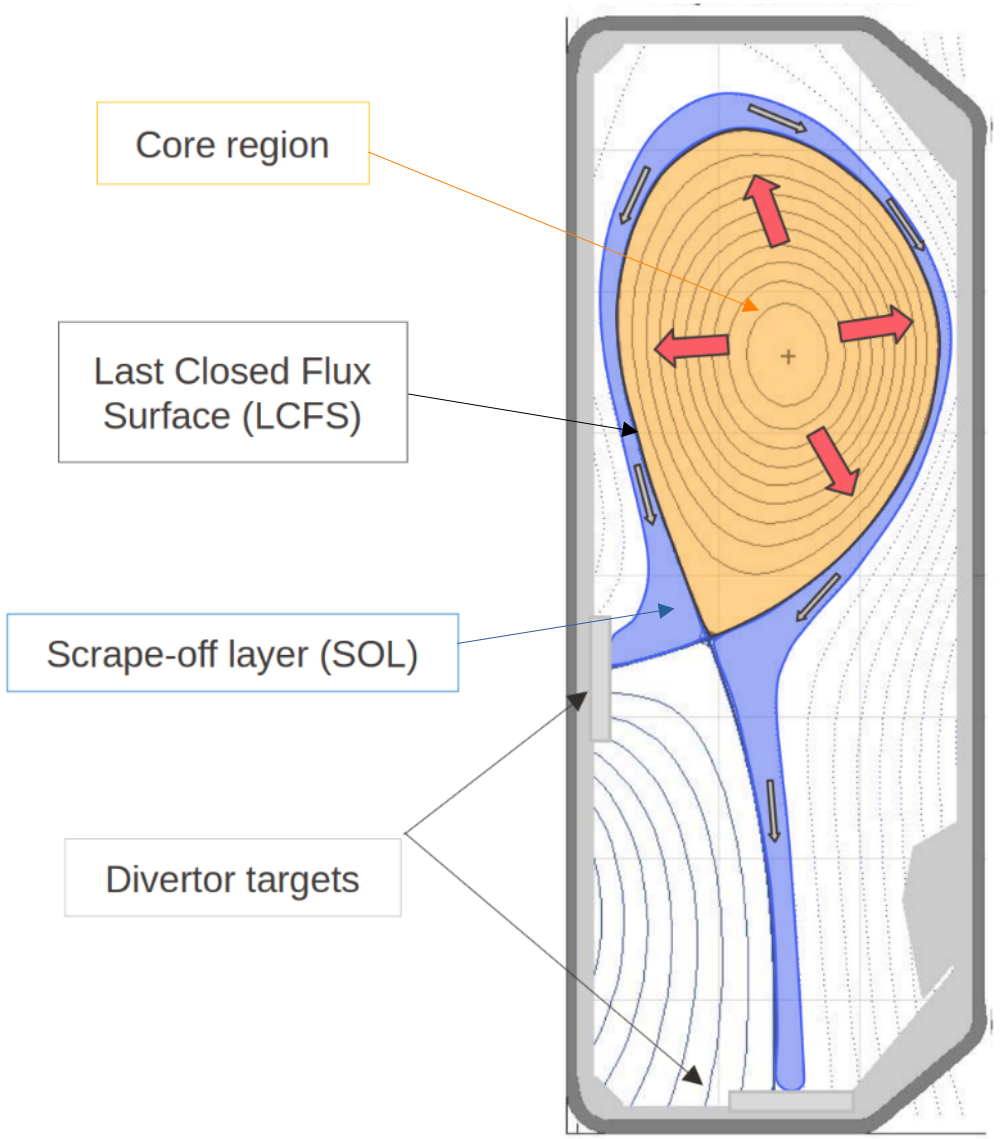


MATLAB service

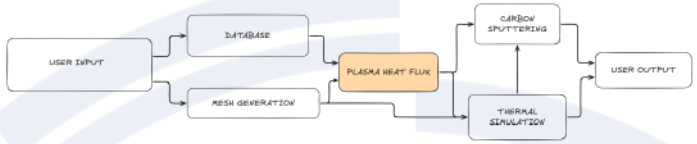
- Allows execution of MATLAB code within the FDT Python environment through MATLAB engine API for Python
- Multiple users can share the same MATLAB session
- Implements data transfer and conversion between Python and the MATLAB session
- Executes MATLAB commands (defined as string in the Python environment)

```
# write in HDF5 file
matlab_service.executeCommand([path_to_file,data_root_group],\
        commands_dict['write_hdf5_versioned'],\
        parser_inputs={save_hdf5_parser_keys[0]:save_hdf5_parser_keys[0],\
        save_hdf5_parser_keys[1]:save_hdf5_parser_keys[1],\
        save_hdf5_parser_keys[2]:default_tag})
```

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING



The different plasma regions [6]

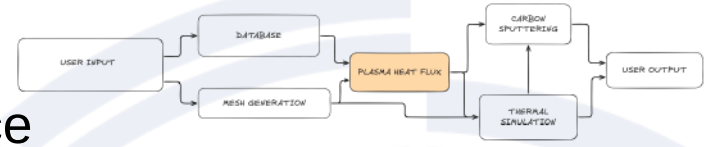


SOL-Fast Surrogate (SOL-FS) service

- SOLPS-ITER is a self-consistent edge plasma-neutral tansport simulation code
- Provides the properties of the edge plasma, which is in contact with the divertor
- It is accurate but not suited for a Digital Twin (too computation-intensive and too many parameters)
- SOL-FS is a Fast Surrogate model that provides fast inferences of the edge plasma properties within a FDT simulation workflow

[6] S. Kerboua-Benlarbi, Scaling and Scarcity: Developing Robust ML Surrogates for Next-Generation Fusion Workflows, PASC26 Conference

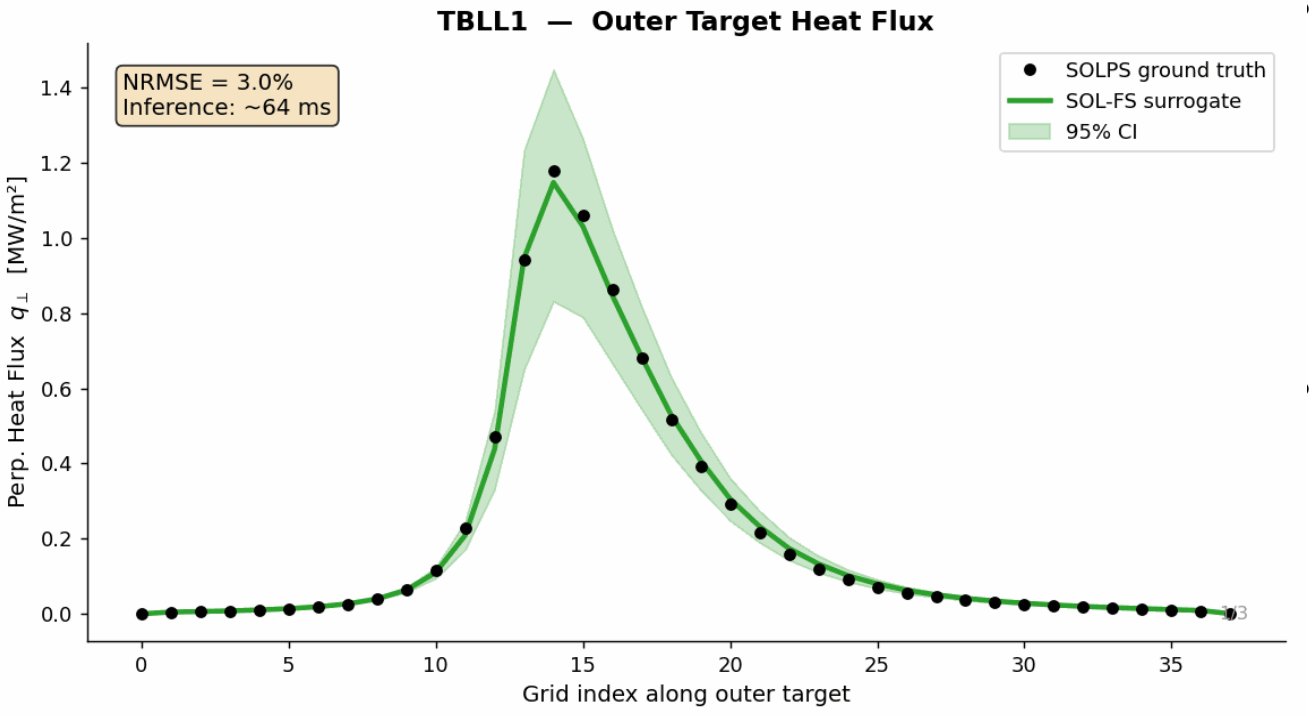
FUSION DIGITAL TWIN: SCIENTIFIC TOOLING



SOL-FS service

SOL-FS can handle multiple configurations (Unbaffled, silo and baffled [TBLL]) but the distance between the baffles is currently discretized for 3 values, for which the results are interpolated using nearest neighbor

The cause of the inconsistencies between SOLFS and SOLPS results in some specific cases has been identified by the very limited number of SOLPS-ITER simulations used for training SOLFS (112 valid samples)



SOL-FS comparison to SOLPS-ITER for various configurations [6]

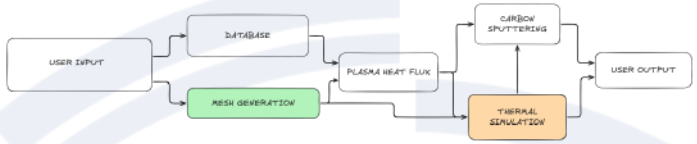
Inputs	SOL-FS	Outputs
Configuration (U, SILO, B1, B2, B3)	→	Total heat flux (W/m²)
Nitrogen seeding (particles/s)		Total particle flux (1/m²)
Hydrogen fueling (particles/s)		
Power from the core to the SOL (kW)		

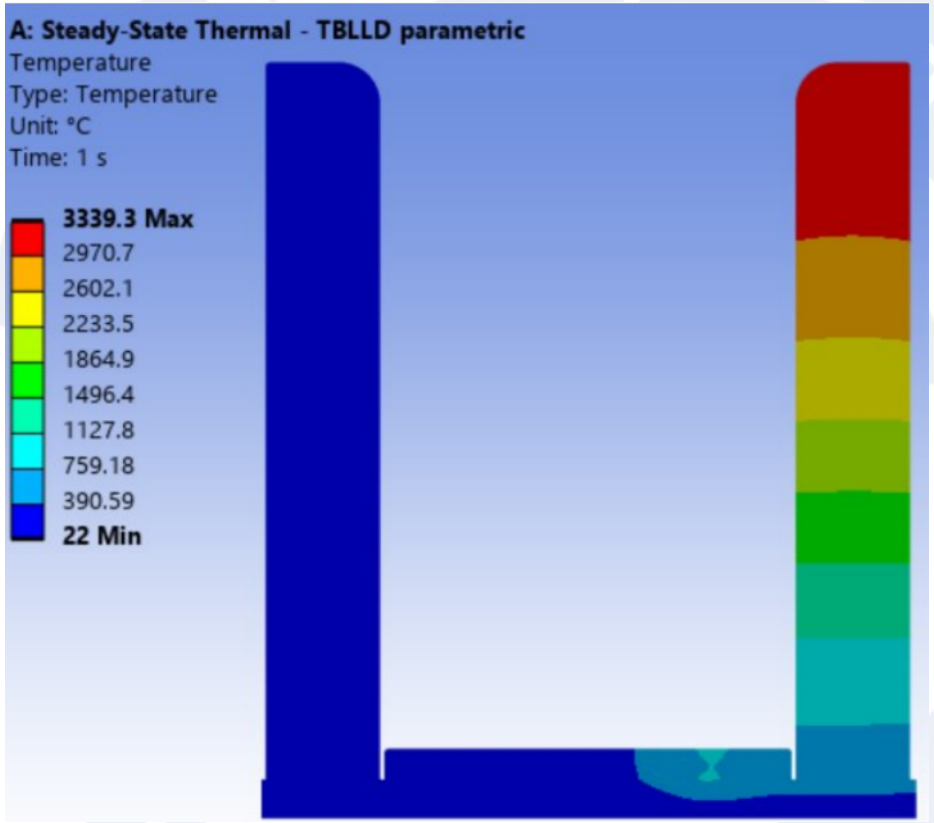
[6] S. Kerboua-Benlarbi, Scaling and Scarcity: Developing Robust ML Surrogates for Next-Generation Fusion Workflows, PASC26 Conference

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING

ANSYS service

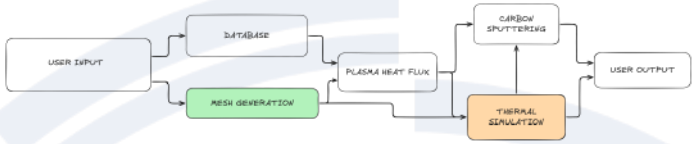
- Instanciates simulation mesh from parametrized geometry based on TBLLD baffle length (DesignModeler)
- Runs steady-state thermal analysis from mesh and heat profile from SOL-FS to output temperature (Mechanical)
- Converts output to visualization-compatible formats (CSV, HDF5, VTK)
- For now, an arbitrary heat sink (20°C at the bottom) models the rest of the wall to allow steady-state analysis





Temperature output of the ANSYS simulation on the TBLLD (K)

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING



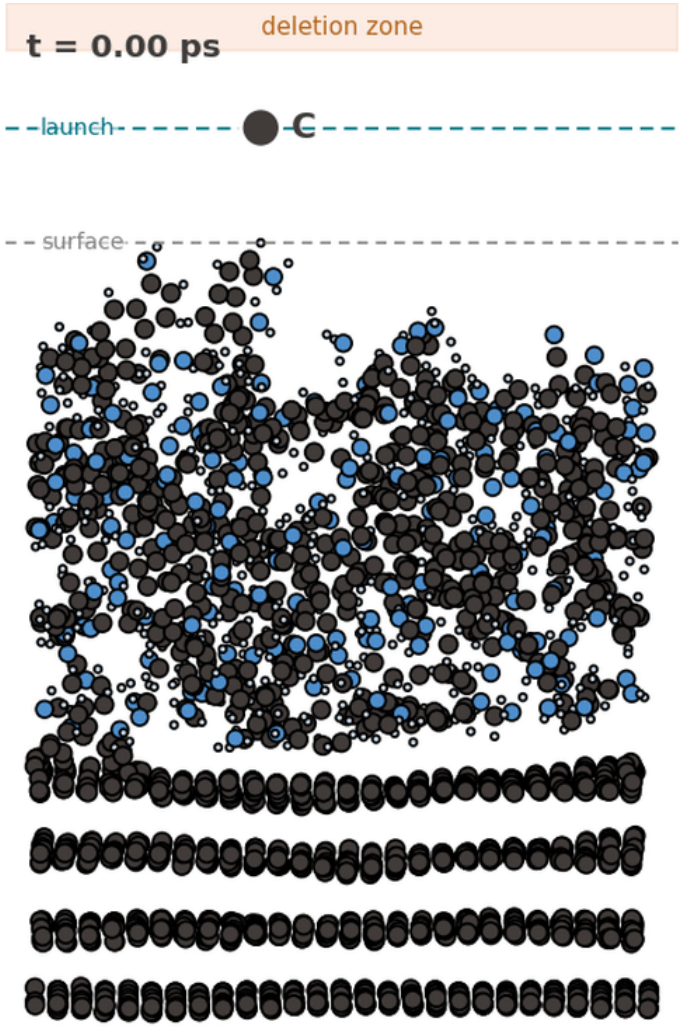
SLURM service

- Python abstraction over SLURM using a job handle
- Jobs have to call scripts from a predefined developer-controlled directory (useful for shared accounts)
- Each job has a dedicated data storage retrievable by its handle (communication between jobs + isolation) ; it can be cleaned up automatically

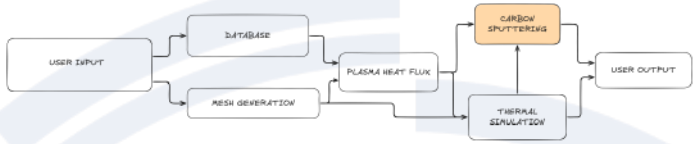
```
from slurm_service import slurm_service
import time

handle = slurm_service.launch_script(["predefined_script.sh", "arg1", "arg2"])
while not slurm_service.status(handle).is_finished():
    print(slurm_service.info(handle))
    time.sleep(10)
print(slurm_service.error(handle)) # stderr
print(slurm_service.files(handle)) # files list in working directory
```

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING



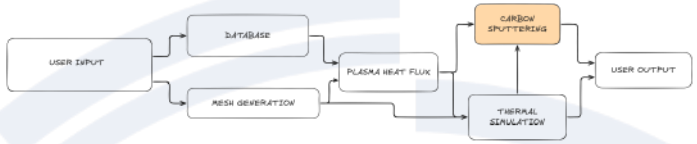
Animation of a 2ps simulation of a bombarded Carbon atom ejecting a plasma H2 particle trapped in the amorphous layer

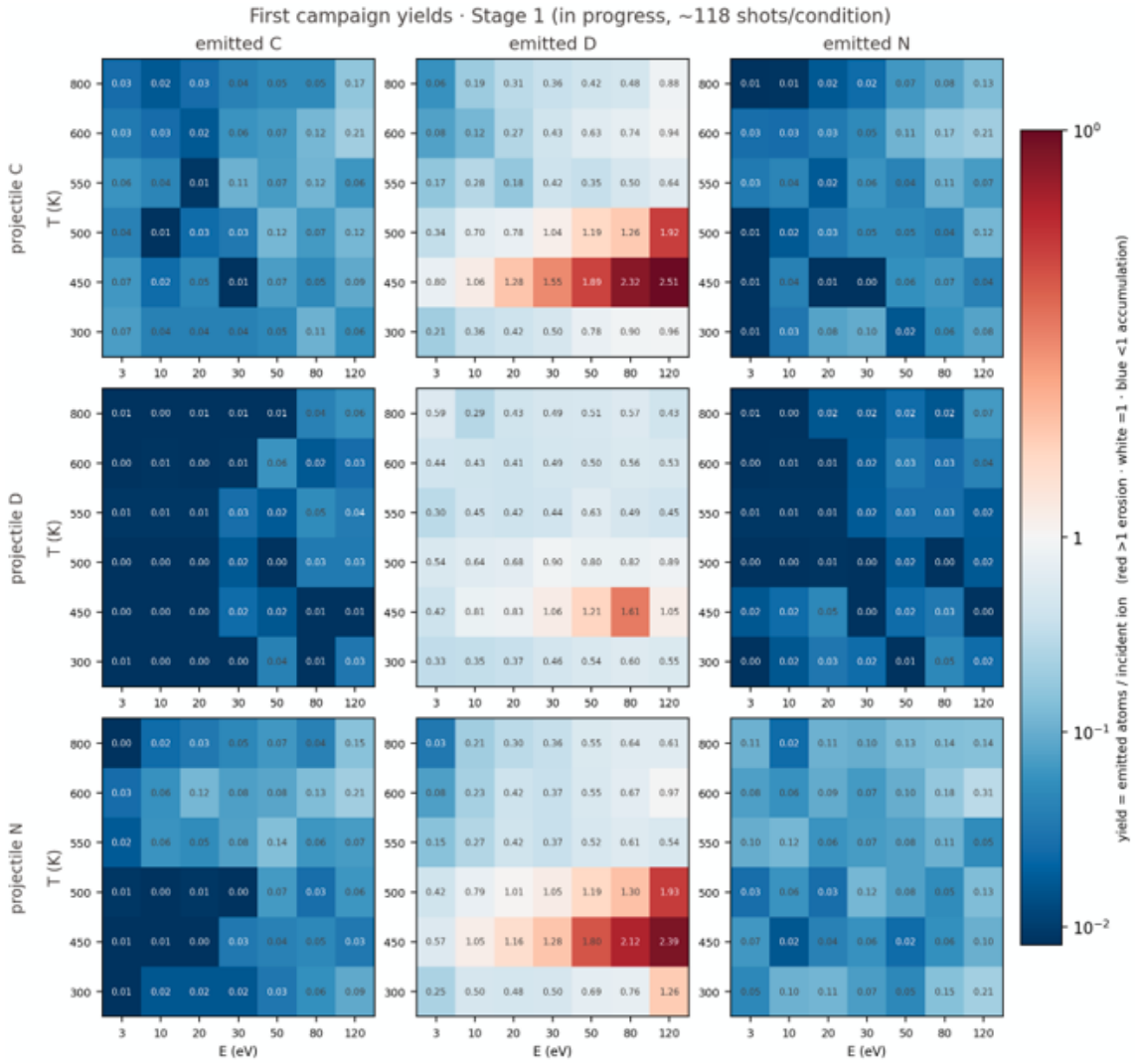


Carbon sputtering service

- Surrogate model of carbon sputtering caused by the plasma bombardment flux at a given temperature of the carbon surface (tile)
- Molecular dynamics with surrogate models for inter-atomic potentials, from Density Functional Theory data
- Emitted impurities may poison and cool down the plasma core leading to performance degradation up to plasma instabilities (e.g. plasma disruptions)

FUSION DIGITAL TWIN: SCIENTIFIC TOOLING



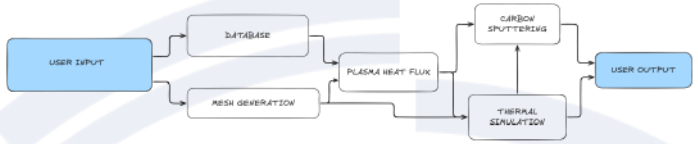


Database of emitted yield as a function of surface temperature and energy of impact, per species

Carbon sputtering service

- Preliminary results show that mostly trapped deuterium is sputtered
- Simulation campaign and interpolator are completed
- In the FDT context:
  - inputs: heat/particle flux from SOL-FS; temperature from Ansys
  - output: carbon sputtering yield (emitted atoms / incident ion), and energy/angle distribution of the emitted particles

FUSION DIGITAL TWIN: NVIDIA TOOLING



NVIDIA Omniverse Kit

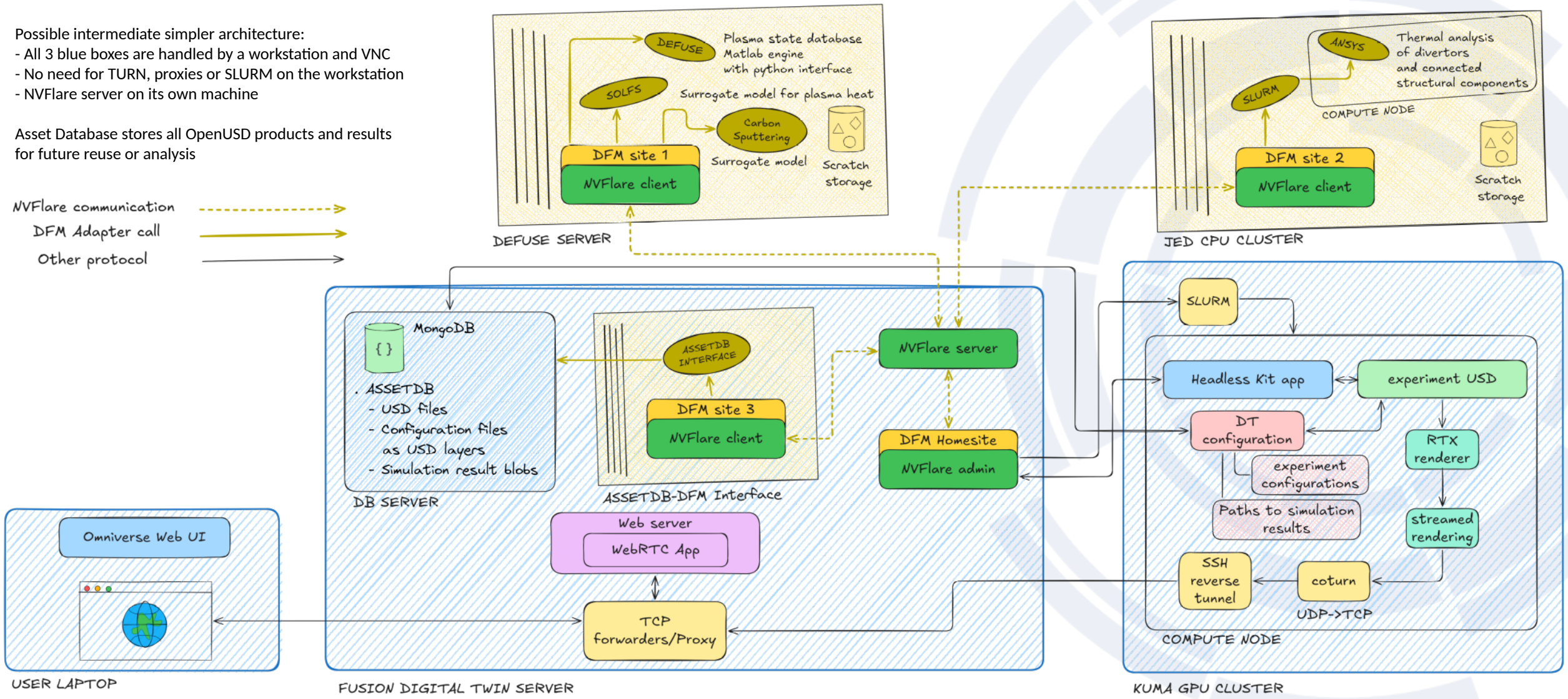
- Modular SDK and application framework
- Used to build OpenUSD-based tools (Universal Scene Description)
- Core capabilities include: scene handling, RTX rendering, UI development, scripting, plugins
- For the FDT, we build a Kit Application to handle the front-end part of the Digital Twin (UI, rendering, file interaction with final products of the FDT)
- We chose to build a web interface with streamed rendering for ease of access from users and to make use of HPC clusters (low hardware requirement on the user side)

NVIDIA Kit Overview - https://docs.omniverse.nvidia.com/kit/docs/kit-manual/latest/guide/kit_overview.html

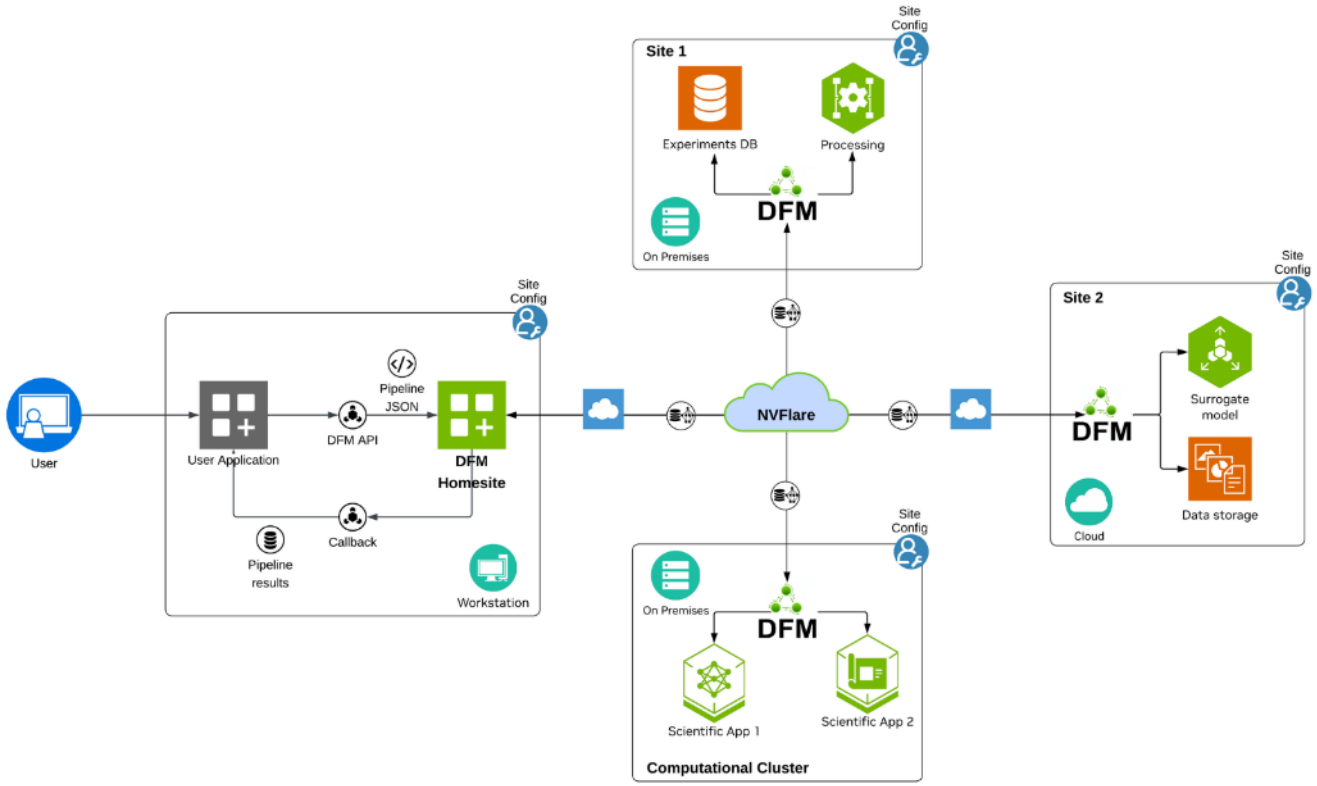
FUSION DIGITAL TWIN: ARCHITECTURE

Possible intermediate simpler architecture:
- All 3 blue boxes are handled by a workstation and VNC
- No need for TURN, proxies or SLURM on the workstation
- NVFlare server on its own machine

Asset Database stores all OpenUSD products and results for future reuse or analysis



FUSION DIGITAL TWIN: NVIDIA TOOLING



Data Federation Mesh example architecture [7]

NVIDIA Data Federation Mesh

- Framework for federated/distributed data-processing orchestration
- Built on top of NVIDIA Flare, it can run high-level distributed programmable pipelines over multiple sites
- It handles data transfer transparently from the pipeline's point of view
- Allows in-site computations preventing the transfer of potentially sensitive data

[7] NVIDIA Data Federation Mesh - https://github.com/NVIDIA/data-federation-mesh

FUSION DIGITAL TWIN: NVIDIA TOOLING

```python
class GenerateGeometry:
    def __init__(self, site: Site, provider: Provider | None):
        self._site = site
        self._provider = provider

    async def body(self, length: int, unit: str) -> str:
        from time import sleep
        from slurm_service import slurm_service

        job_handle = slurm_service.launch_script(["generate_geometry.py", '[' + length + ']', unit])
        while not slurm_service.status(job_handle).is_finished():
            print(job_handle, "Files generation running...")
            sleep(1)
        print("Files generation finished with status:", slurm_service.status(job_handle))
        return job_handle
```

```python
with Pipeline() as p:
    # Generate ANSYS geometry from given length
    geom_job = GenerateGeometry(site=ansys_site, length=length, unit='mm')

    # Get the generated vertices of the geometry
    vertices = GetVertices(site=ansys_site, job_handle=geom_job)

    # Run SOLPS Surrogate neural network to compute heat profile from plasma state for every vertex
    heatflux = SOLFSComputeHeatFlux(site=defuse_site, length=length, unit='mm', vertices=vertices)
```

Developer provides functionality to the DFM through the adapter API, which body becomes callable from the DFM programmable pipeline written in a Pythonic domain specific language

In this example,

the GenerateGeometry adapter instanciates the geometry using the SLURM/ANSYS services
It can then be called like a function in the pipeline at a given site

FUSION DIGITAL TWIN: NVIDIA TOOLING

SPC / Fusion Digital Twin / **Fusion Digital Twin Tutorials**

master fusion-digital-twin-tutorials / **DFM**

DFM

Publish a provisional chapter 4
Florian Cabot authored 2 weeks ago

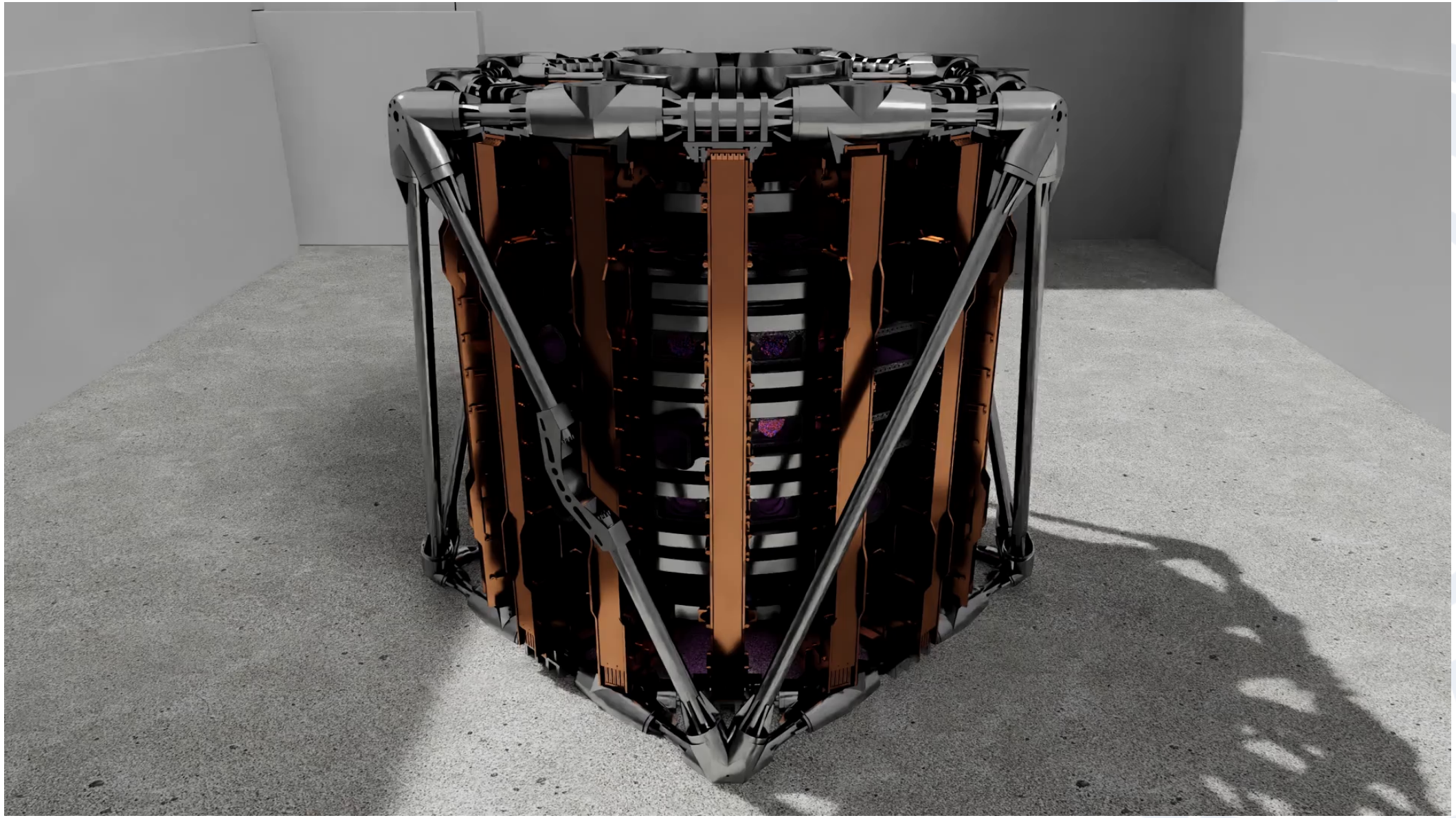
Name	Last commit
..	
00_Introduction_to_the_Data_Federation_Mesh	Apply clarity/typo additional fixes
01_Installation	Apply clarity/typo additional fixes
02_Federation	Cleanup
03_Operations_and_Adapters	Cleanup
04_Application_and_pipelines	Publish a provisional chapter 4
A_The_Fusion_Digital_Twin	Publish Appendix B
B_Automating_the_Fusion_Digital_Twin	Publish Appendix B
.env.example	Finish chapter 01
.ssh-config.example	Apply clarity/typo additional fixes
README.md	Publish Appendix B

Data Federation Mesh tutorials by EPFL (F. Cabot)

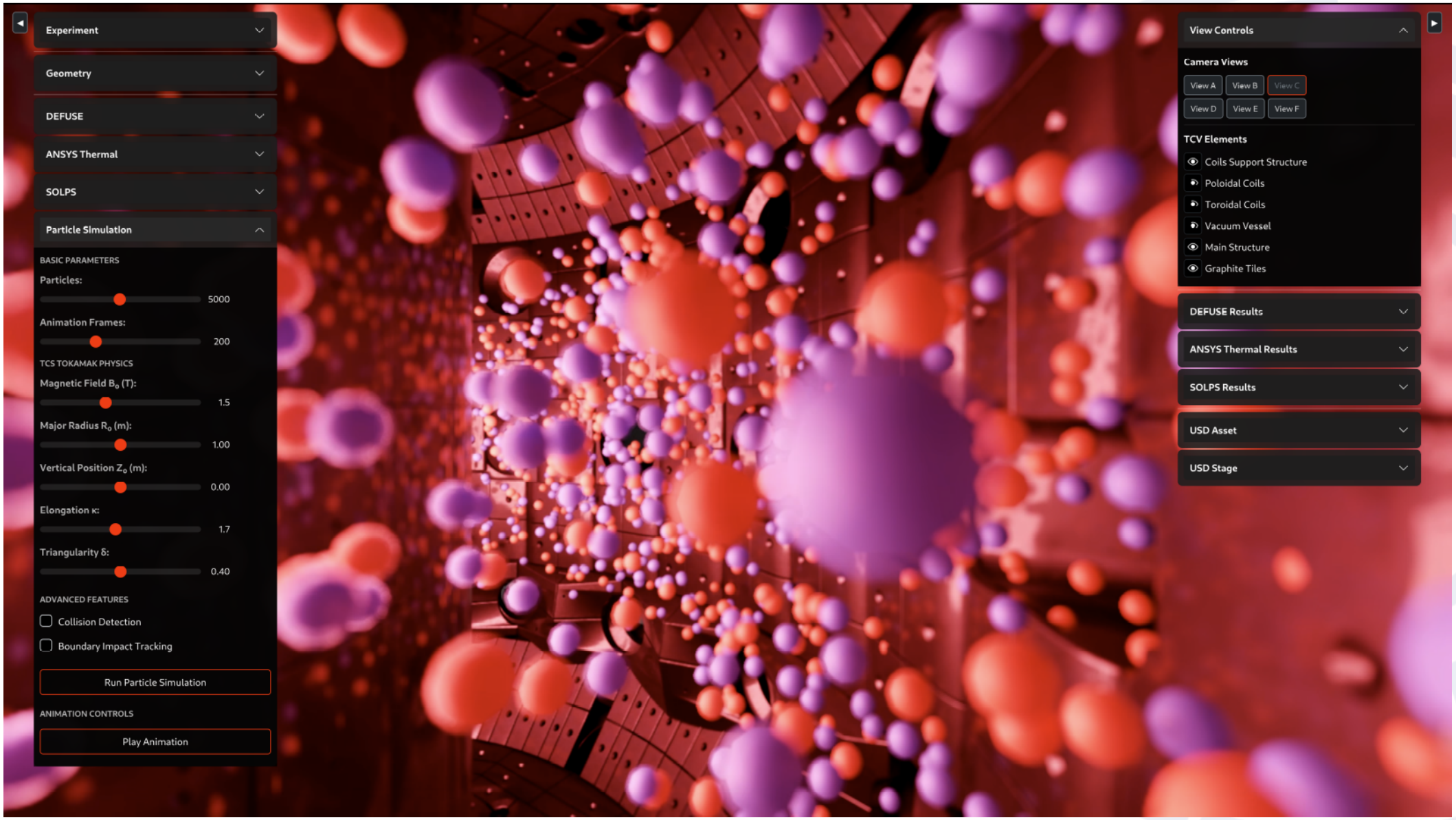
FUSION DIGITAL TWIN: VISUALIZATION

- Visualization runs inside of the Kit Application, which includes a renderer for OpenUSD scenes stored in an asset database
- These scenes can be produced on the fly on the rendering machine or within another FDT service
- A light physics simulation (such as particle dynamics or magnetic field reconstruction) can be ran on the client GPU from DEFUSE-retrieved data (using for example WARP or CuPy for GPU acceleration), its result stored in an OpenUSD file, then displayed as an animation in the Kit Application
- Real-time simulation at rendering time can also be done with GPU shaders

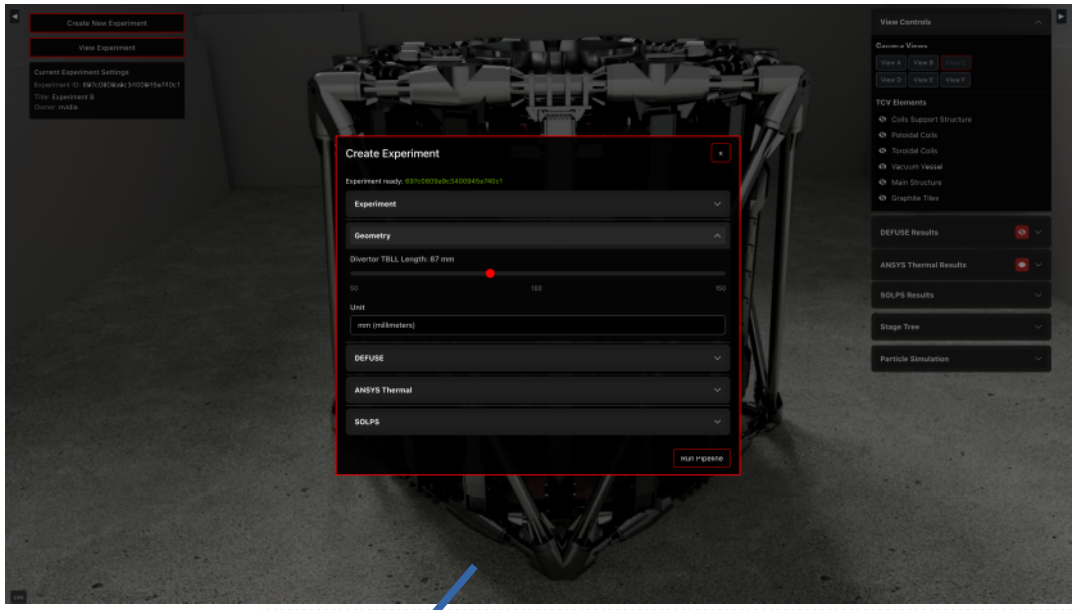
FUSION DIGITAL TWIN: VISUALIZATION RESULTS

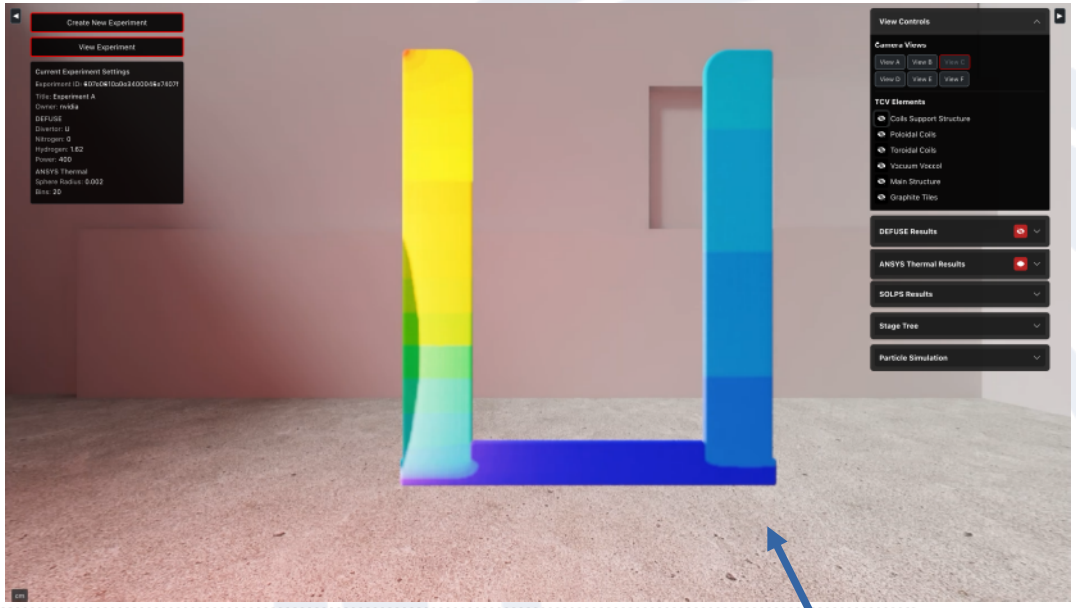


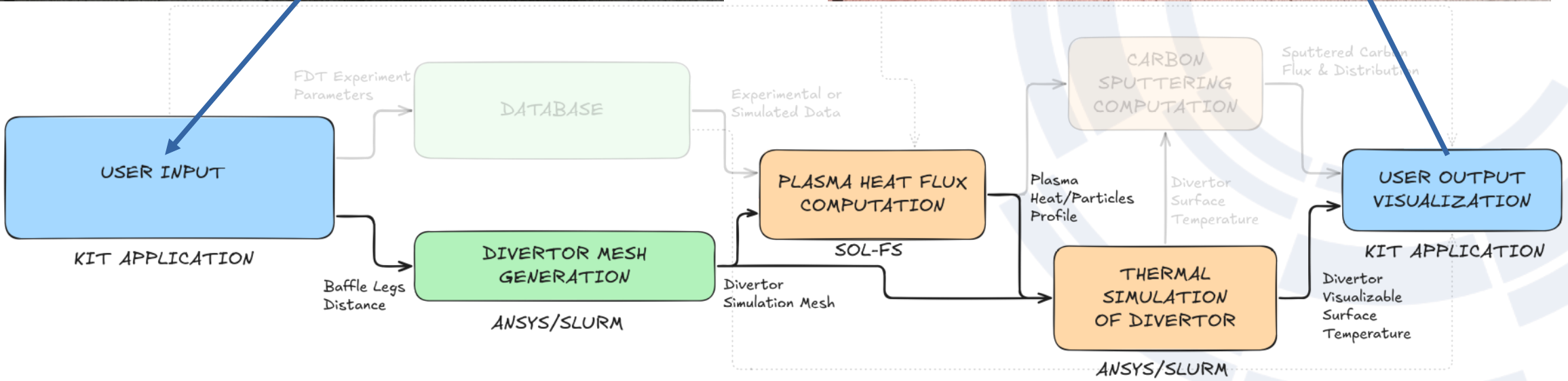
FUSION DIGITAL TWIN: WEB-BASED USER INTERFACE



FUSION DIGITAL TWIN: COMPLETED PROOF OF CONCEPT








CONCLUSION

CONCLUSION

- Proof of Concept of the EPFL/NVIDIA Fusion Digital Twin is operational
- Possible to execute a full simulation pipeline with a minimum set of tools (SOL-FS/ANSYS/SLURM/Kit)
- The simulation pipeline can run on multiple sites, even across different networks
- Reading and writing data with DEFUSE is operational but not fully integrated
- Visualization and real-time small simulations have been demonstrated

The first full implementation of the EPFL/NVIDIA Fusion Digital Twin is almost complete!

FUTURE WORK

- Finalize and integrate all remaining services with testing
- Fully implement streaming architecture (separate POC now fully works on Kuma)

Short term goals:

- ANSYS: Introduce full 3D thermo-mechanical simulation of TCV first wall
- SOL-FS: Move away from discrete baffle length with a continuous model and enrich the database with multiple plasma states and divertor geometries
- Carbon Sputtering: Implement the FDT service

- Extend simulation capabilities (until end of 2027):
  Heat load due to : plasma radiation (radiation in SOLFS + ray tracing)
  fast particles impacts on first walls (ASCOT + GEANT4)
  Introduce synthetic diagnostics for comparison against experiments
  Explore drone training using FDT to inspect TCV (F. Giglio, A. Mele)

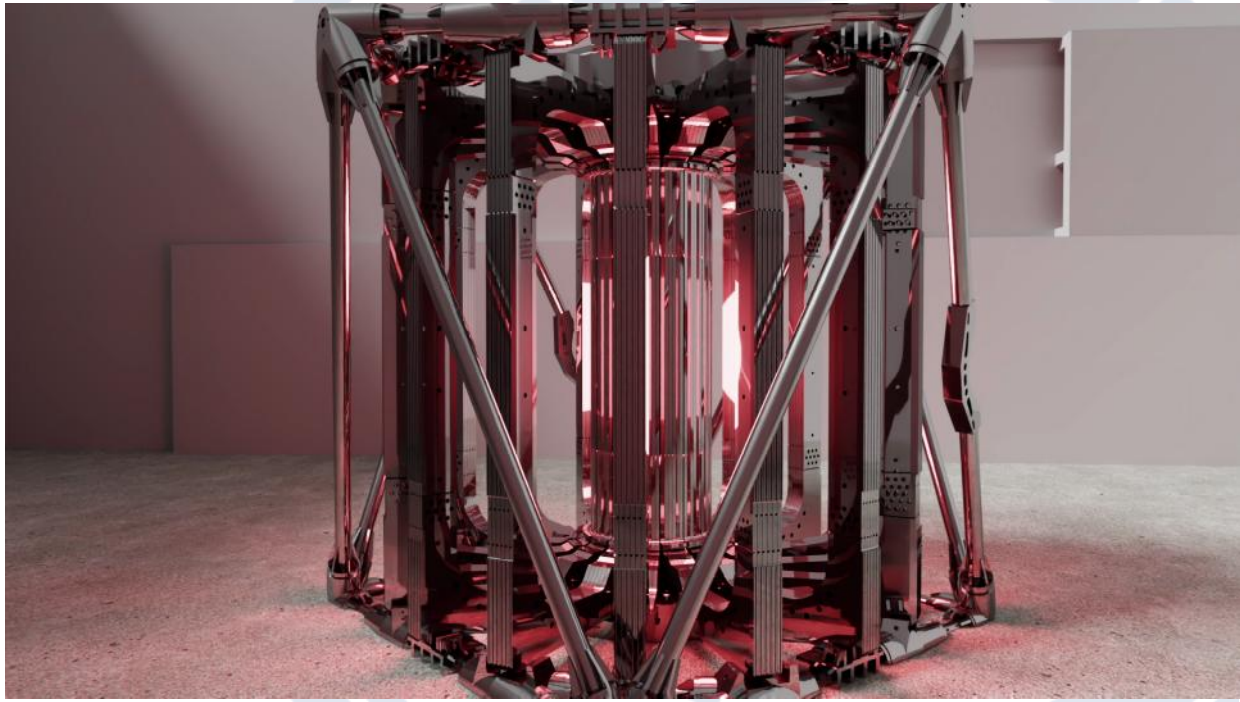
October 27th 2026
4th Annual Meeting of EUROfusion HPC ACHs

The Fusion Digital Twin: Integrating Databases, Simulation, AI Surrogates and Visualization for Design Workflows of Fusion Devices

Florian Cabot, N. Litchinko, N. Richart

C. Sommariva, S. Kerboua-Benlarbi, H. Elaian, M. Toussaint, A. Pau, P. Blanchard, H. Reimerdes, O. Sauter, E.Tonello, C. Yildiz, A. Fedrigucci*

D. Fransos, C. Angerer, C. Favreau, F. Yang, S. Duthaler, J. Zielinski



THANK YOU

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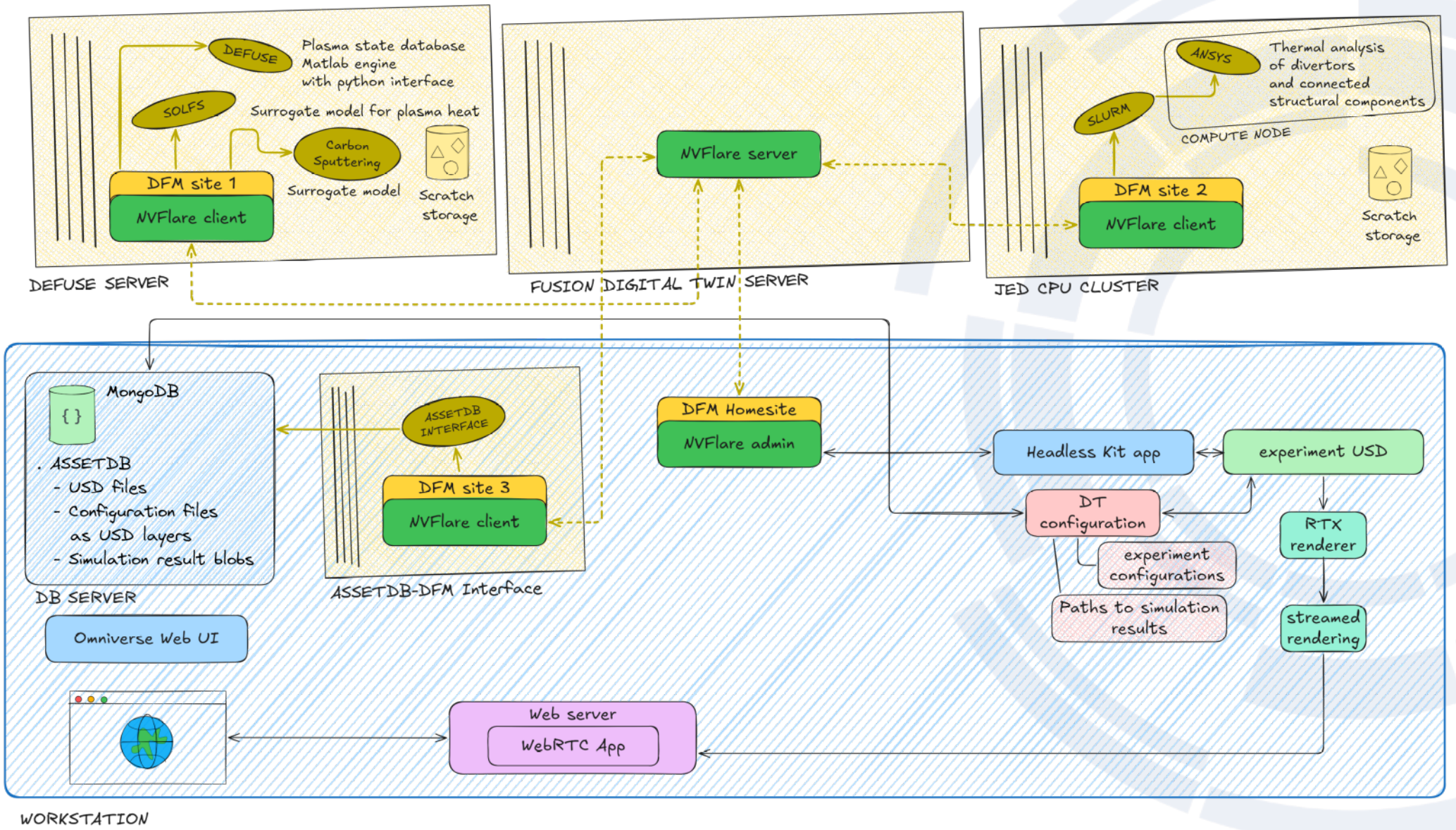
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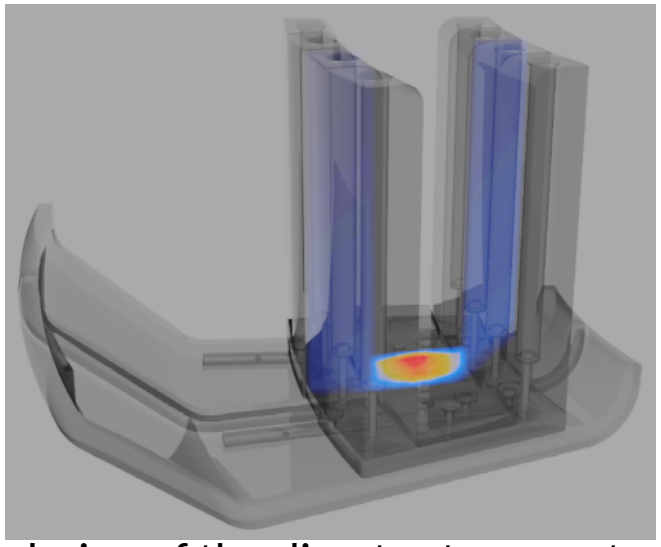
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BACKUP

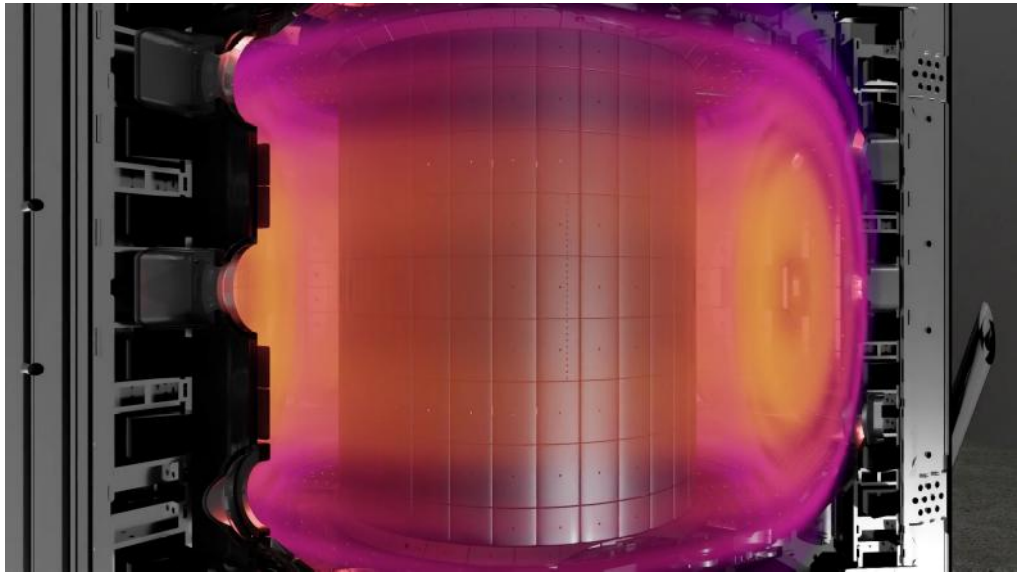
FUSION DIGITAL TWIN: INTERMEDIATE ARCHITECTURE



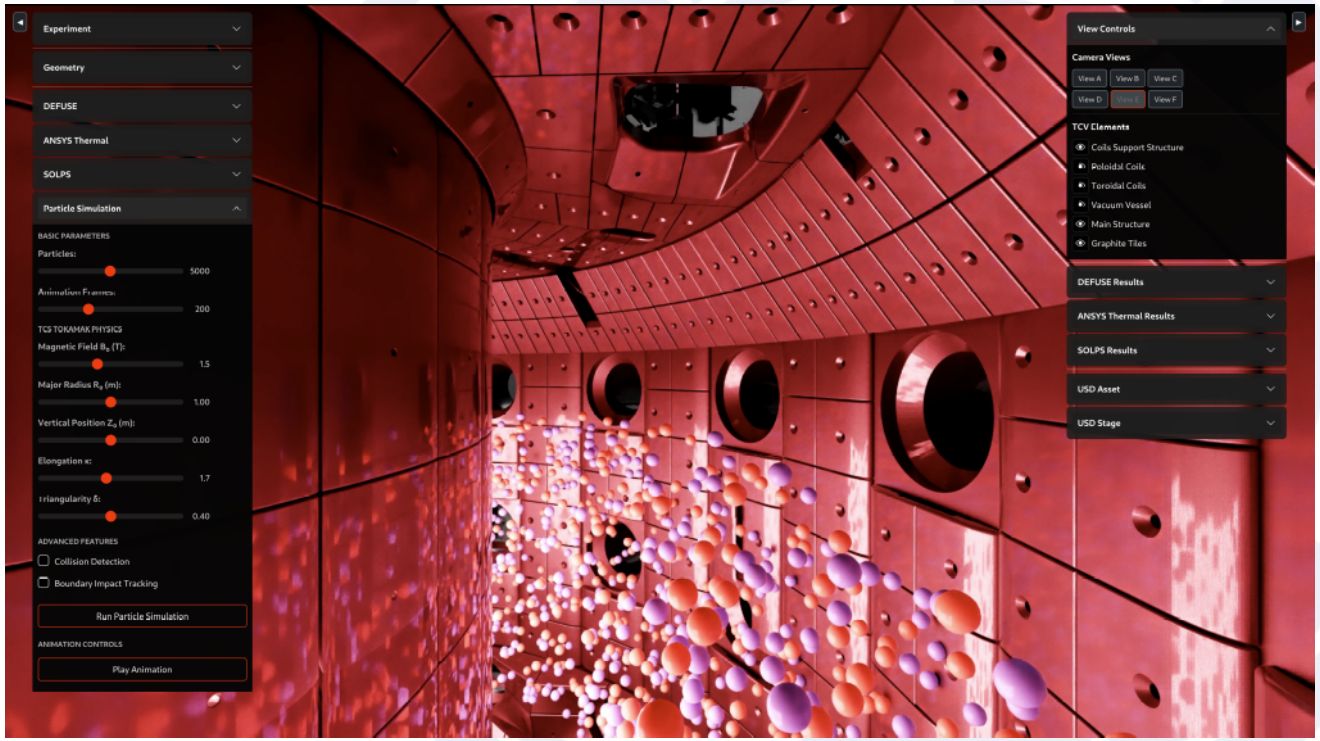
FUSION DIGITAL TWIN: PRELIMINARY VISUALIZATION RESULTS



Rendering of the divertor temperature profile



Volumetric rendering of the magnetic field



Particle dynamics simulation in the 3D model of TCV