Development of Virtual KSTAR: Scientific Visualization and Beyond for Fusion

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on behalf of V-KSTAR Development Team

Korea Institute of Fusion Energy

AI and Data Vis Workshop
June 13. 2024

TriTech
Virtual.Art.Clean

POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

서울대학교
SEOUL NATIONAL UNIVERSITY

UNIST

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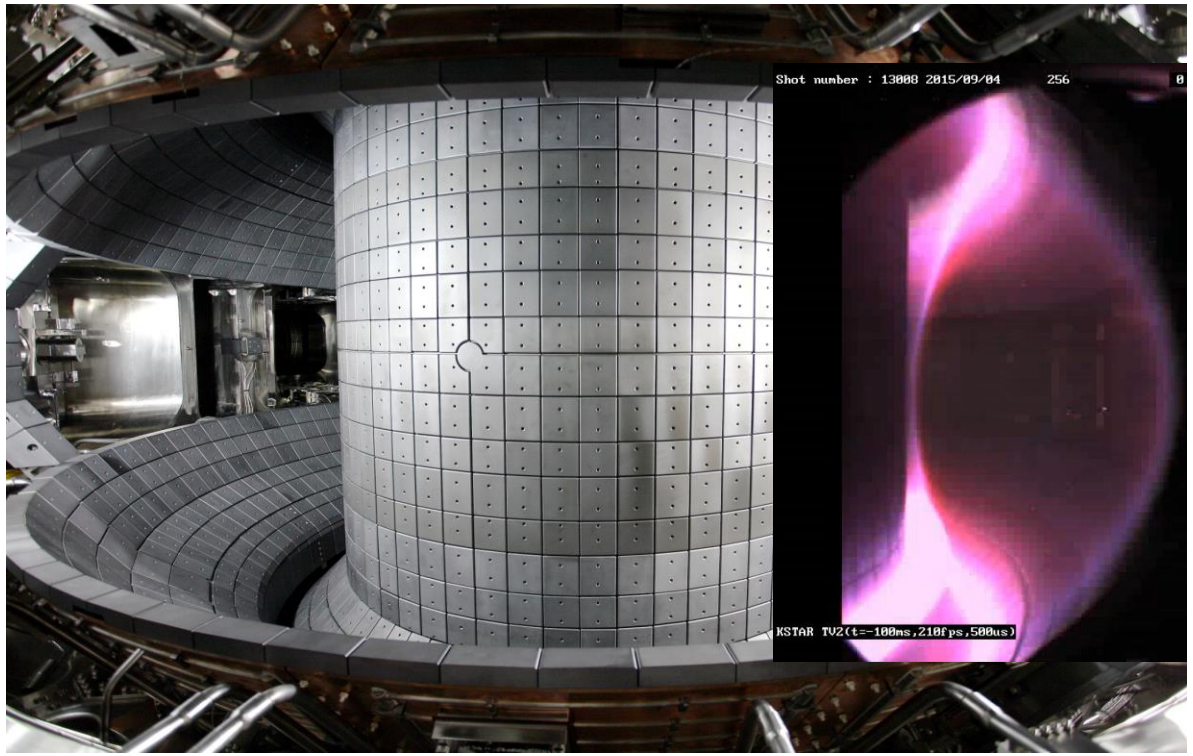
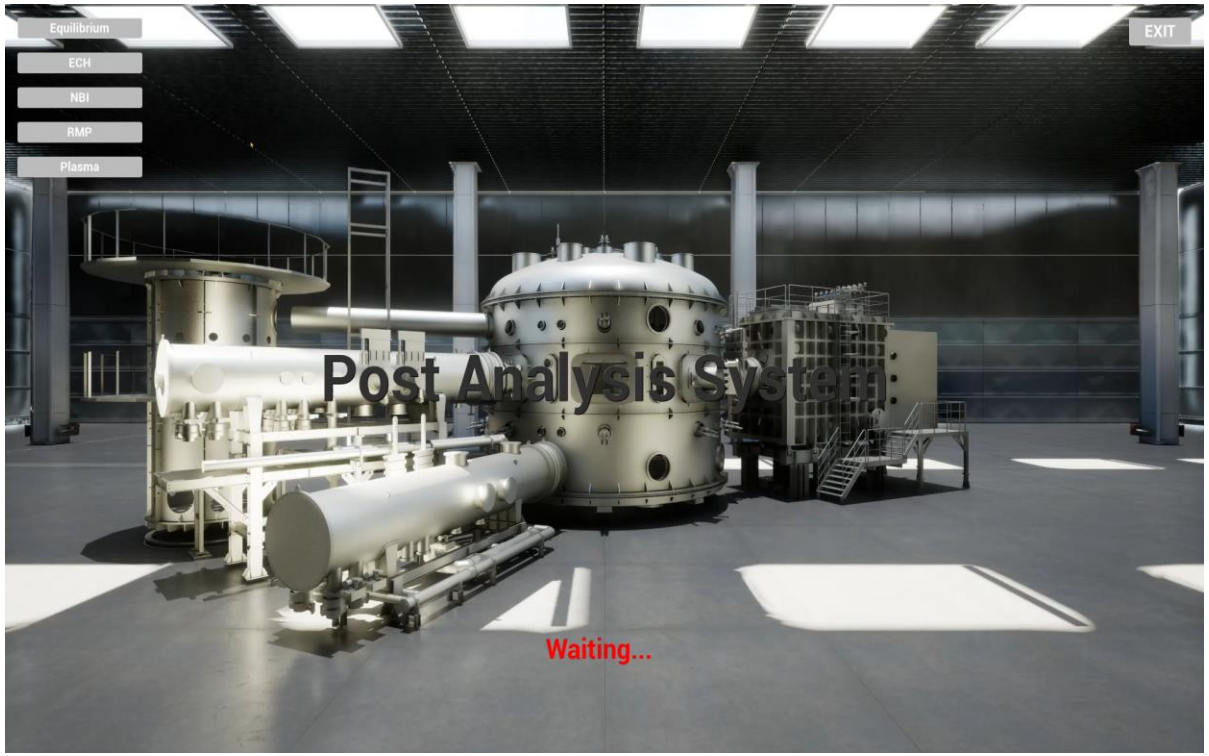
KOREA INSTITUTE OF FUSION ENERGY

Digital Twin Technology

- Collection of IT technologies to virtualize the shape and function of objects with varying degrees of sophistication
  - Level 1: virtualize the shape of real object with some minimal data, properties
  - Level 2: connected to measured data obtained from operation of real objects
  - Level 3: integration of simulation, analysis capabilities based on AI/ML etc.





Contents

Enabling Technologies for Fusion Digital Twin

한국핵융합에너지연구원
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Jae-Min Kwon et al, "Development of a Virtual Tokamak platform", Fusion Eng. Des. 184, 113281 (2022)

Jae-Min Kwon et al, "Progress in Digital Twin Development of Virtual Tokamak Platform", accepted to IEEE Trans. Plasma Sci. ; also see SOFE2023

Enabling Technologies – 3D Algorithm and Mesh

Virtual Tokamak Control Center

User

Visualization Clients

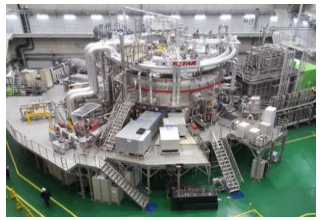
Data Framework (IMAS/IDS)

Graphic Engines

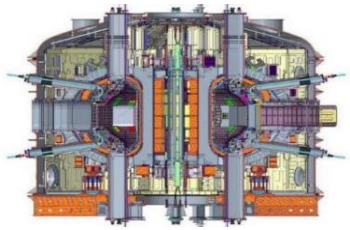
Library for Advanced 3D Algorithm & Mesh

Simulation Data/Code

Experimental Data

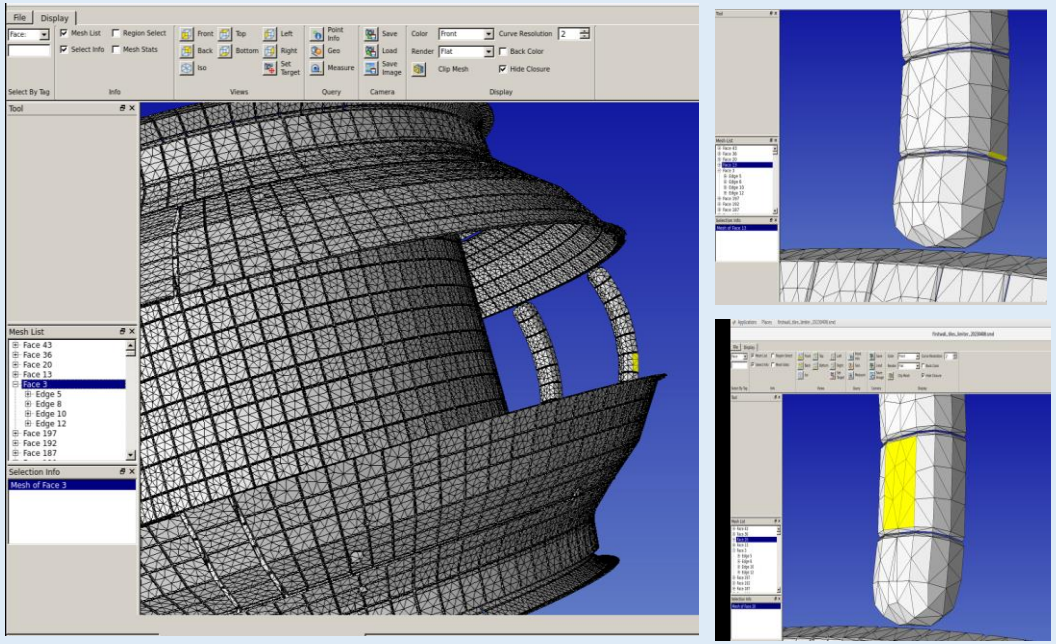


CAD Data



Mesh Technology

- Adaptation of parallel mesh technology developed for US SciDAC project – PUMI library developed by SCOREC in RPI (https://scorec.rpi.edu/pumi/)
  - Unstructured triangular mesh for arbitrarily complex shapes
  - Originally developed for massively parallel simulation
  - Tools for parallel partitioning & load balancing, refinement etc.



Unstructured Mesh Generation

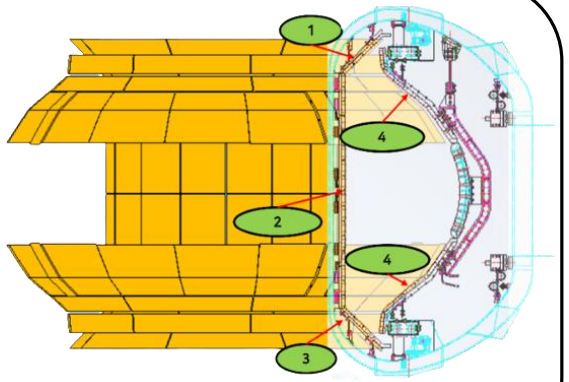
Taeuk Moon, Eisung Yoon, UNIST
Keunsoo Lee, Gahyung Jo, KFE

Mesh Technology

Taeuk Moon, Eisung Yoon, UNIST; Keunsoo Lee, Gahyung Jo, KFE

FPL
Fusion and Plasma application research Laboratory

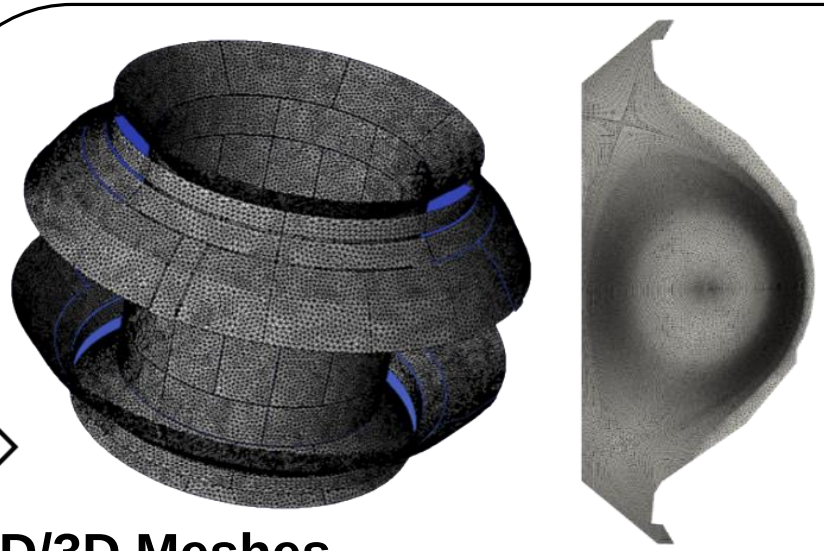
Original CAD Model



Defeatured CAD Model

Baseline Mesh Generation

Visualization Client
- Data Analysis & Recording
- Rendering

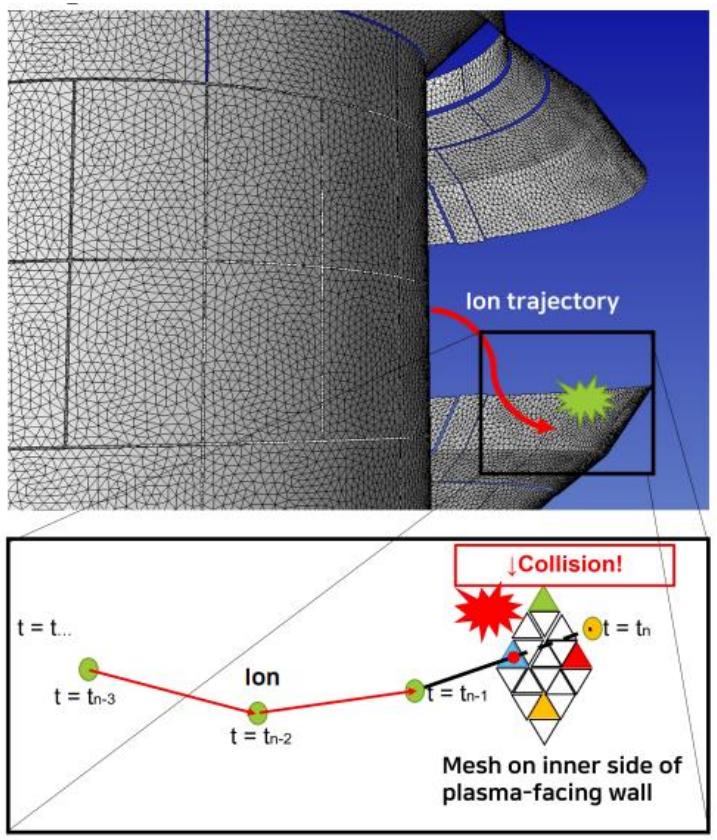


2D/3D Meshes

Fusion Simulation
- Mesh Refinement & Partition
- Parallel Simulation

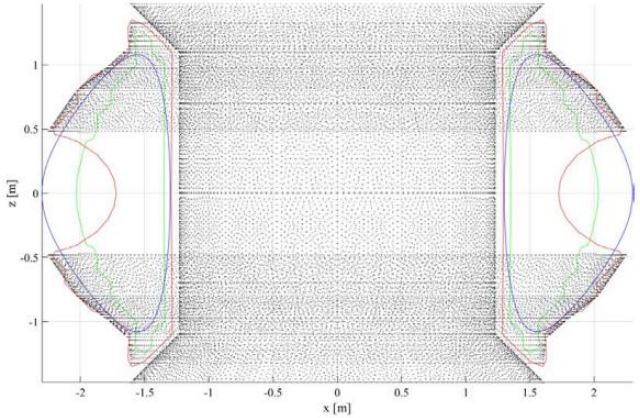
Key to integrate & analyze fusion data on engineering design

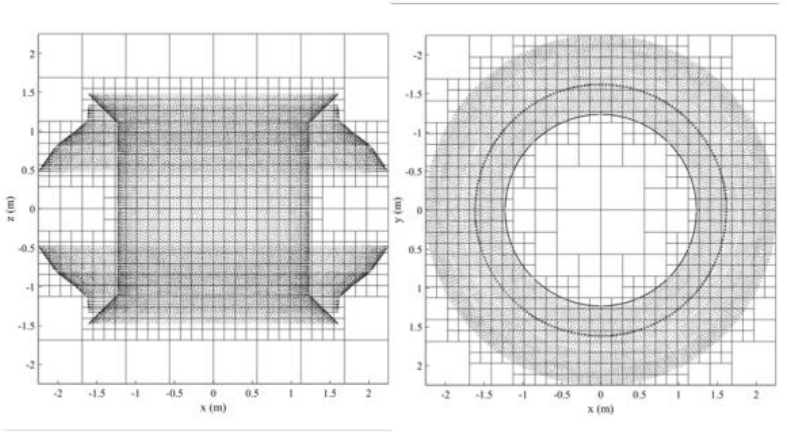
3D Collision Detection & Recording



Schematic diagram of collision detection by ray-casting

- Detection of collisions between dynamically moving objects and machine components (e.g. fast ions injected by NBI)
- 2-phased collision detection: 1) broad phase to narrow down and 2) narrow phase to pinpoint down
- Being developed as general C++ library





Winding number, Hash table, Octree algorithms for collision detection

FPL
Fusion and Plasma application research Laboratory

Taeuk Moon, Tongnyeol Rhee et al, Submitted to Comput. Phys. Commun.

Enabling Technologies – Data Framework (IMAS/IDS)

Virtual Tokamak Control Center

Visualization Clients

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Graphic Engines

Library for Advanced 3D Algorithm & Mesh

Simulation Data/Code

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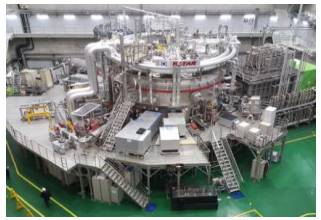

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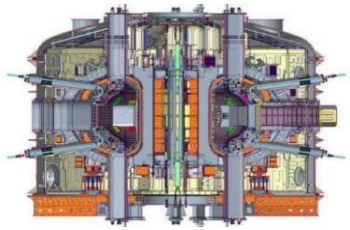
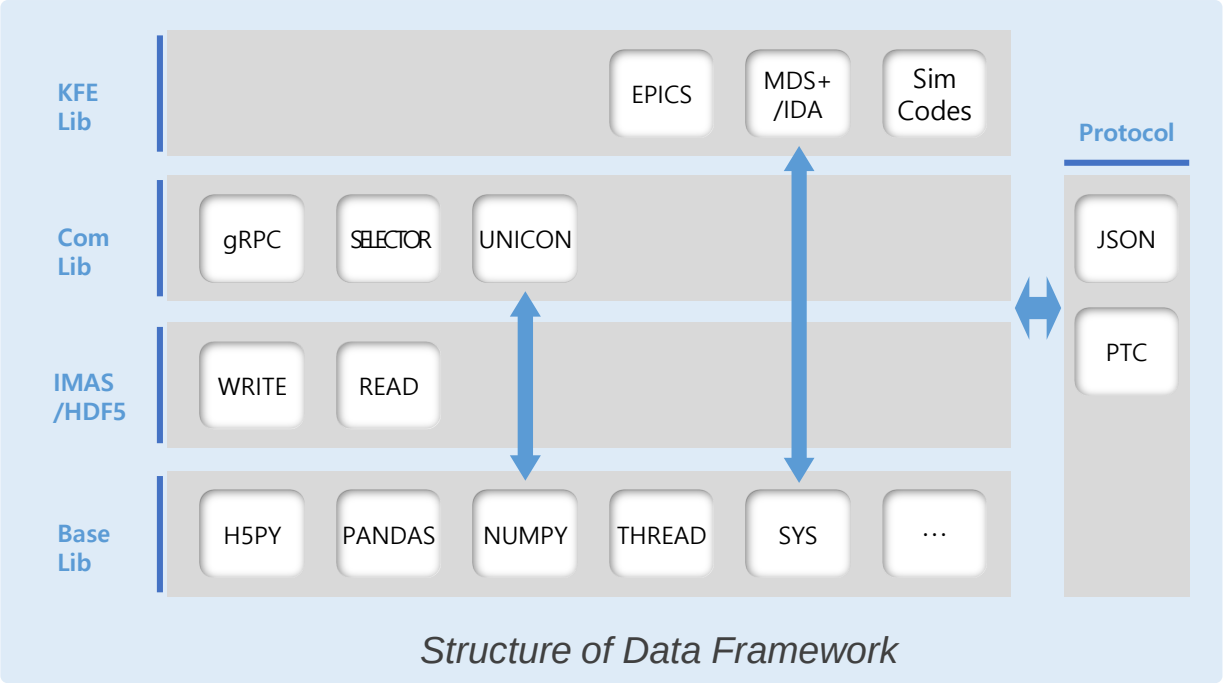


Data Framework

- New Framework dedicated for Fusion Digital Twin
  - ITER-IMAS & HDF5-based unified format
  - Python & C++ as primary development languages
  - Provide APIs for legacy formats – MDS+, EPICS, etc

Dajung Kim, Chanjong Lee, Hosaeng Choi, Jaesuk Ki, Tri-Tech
Sangjin Park, Myungsub Jun, SNU; Chanyoung Lee, KFE



Structure of Data Framework

Enabling Technologies – Graphic Engine & Visualization

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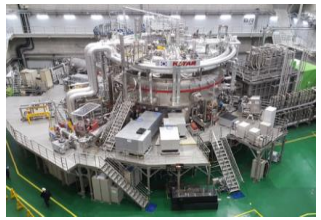

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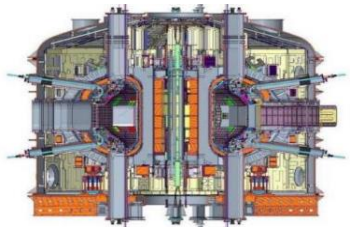
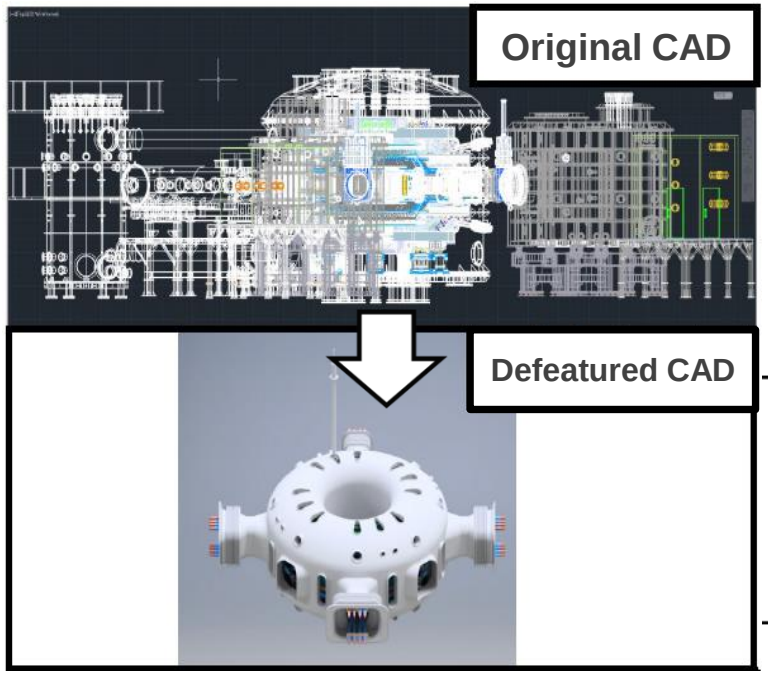
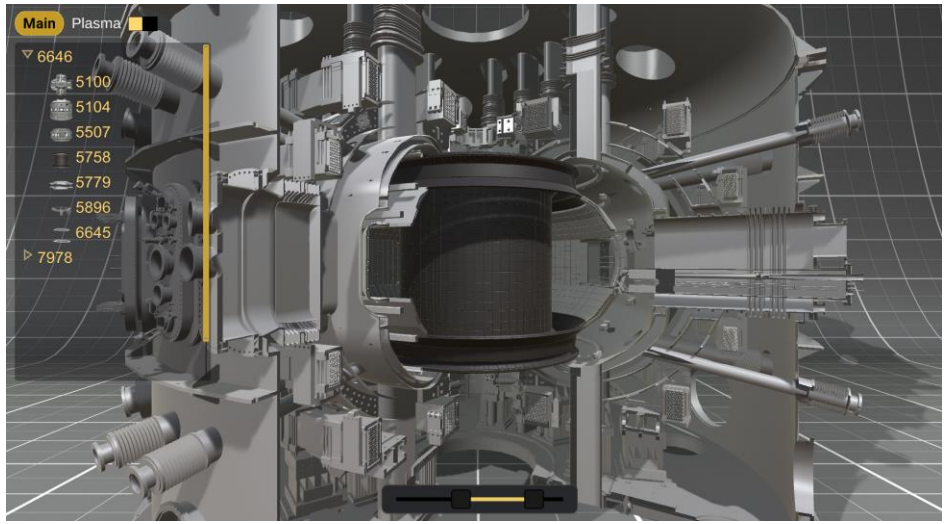


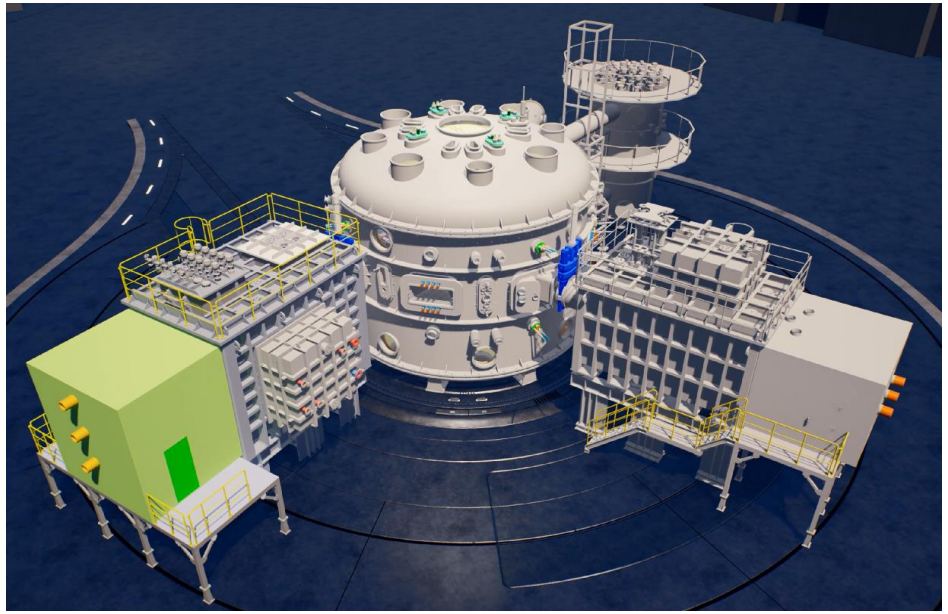
Graphic Engine for Visualization



- Format Conversion
- Re-Grouping of Models

Made with unity

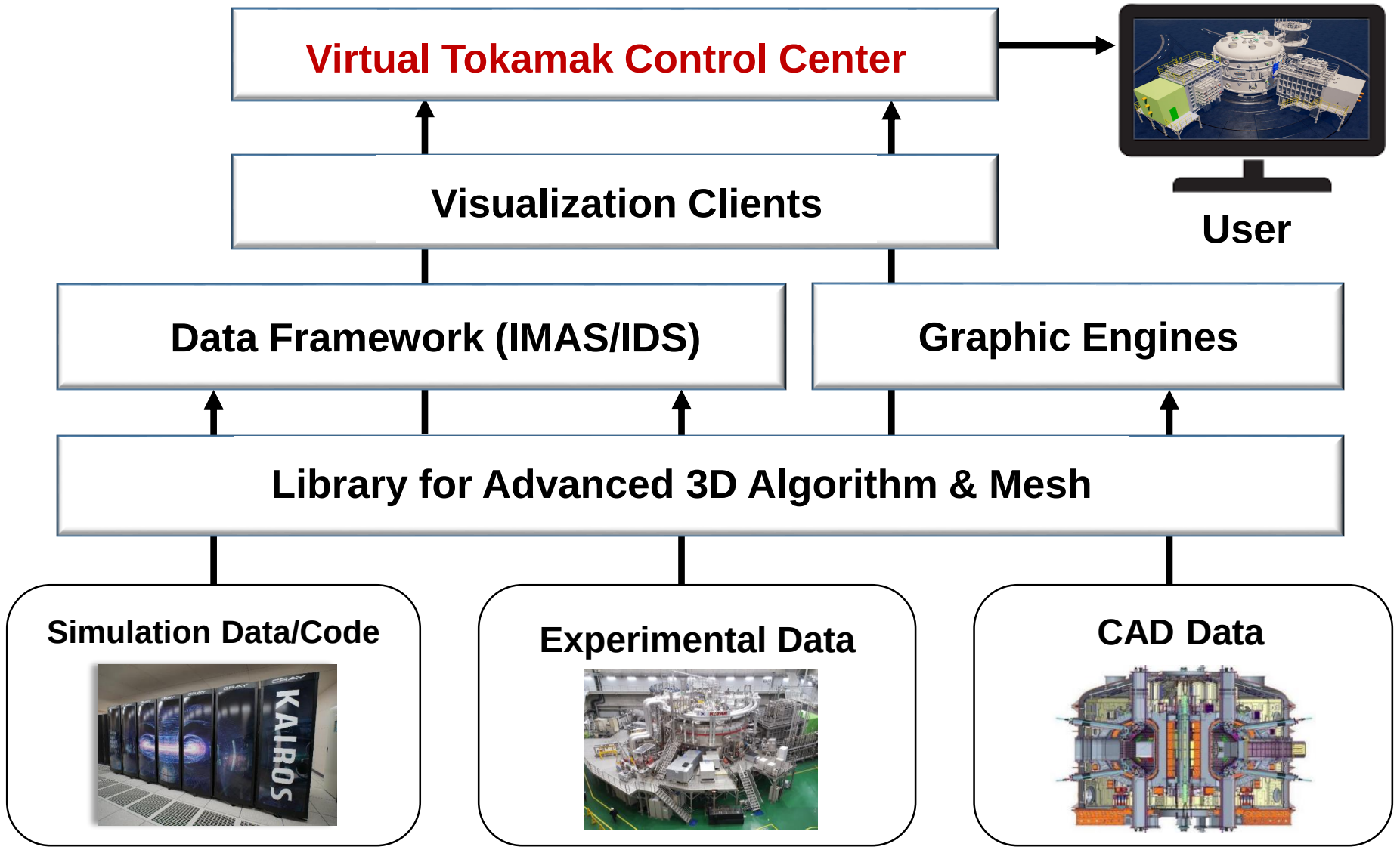




- Two graphic engines are utilized:
  - Unity → Light application running on relatively modest computing resource e.g. laptop, mobile
  - Unreal → Higher graphic quality, but require more powerful computing resource i.e. good graphic cards

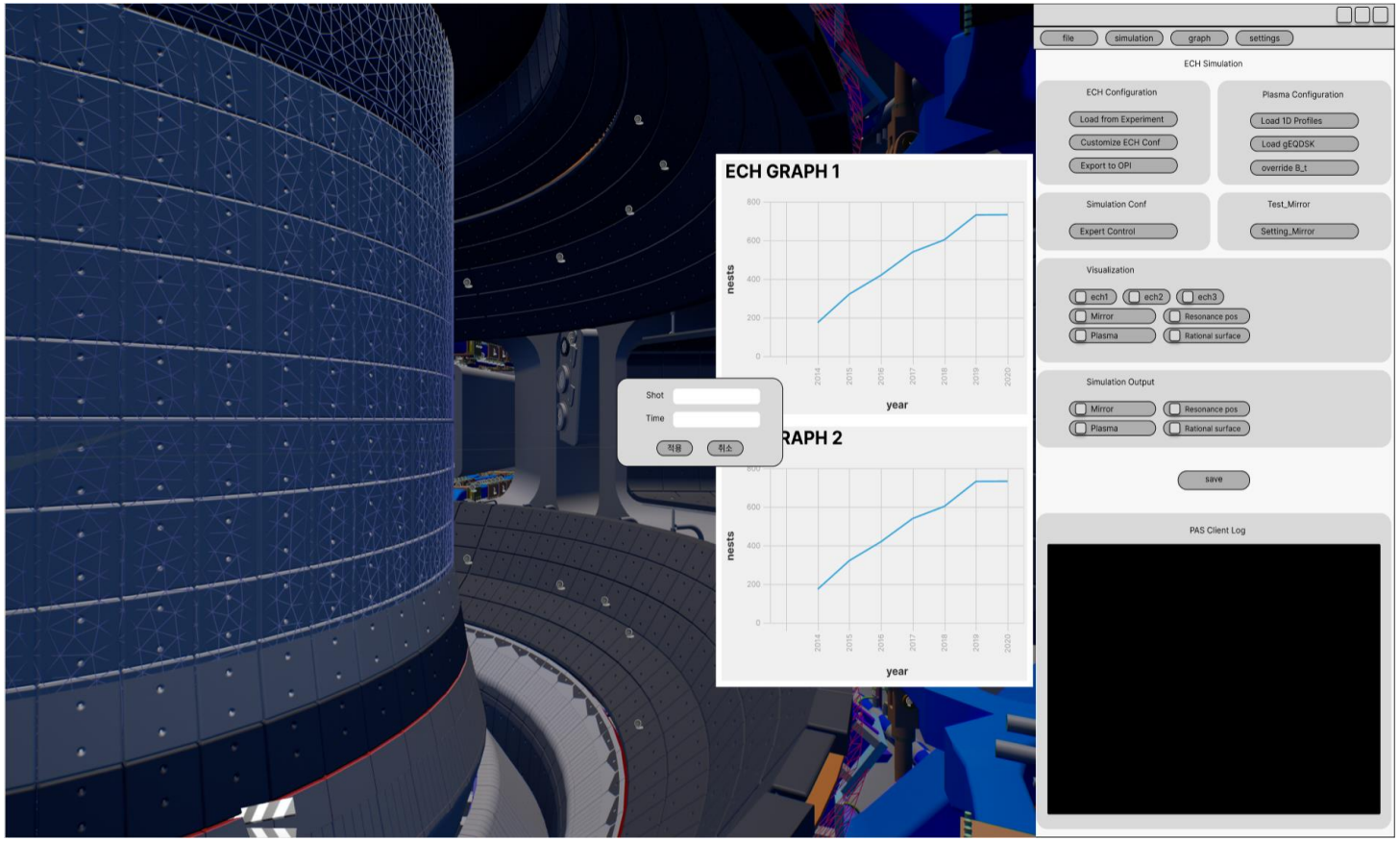
UNREAL ENGINE

Enabling Technologies for Fusion Digital Twin



Interfacing Data Framework & Visualization Client

- Virtual Tokamak Control Center (VCC)
  - Python application & library for data management in virtual platform
  - Communication with visualization client via socket communication
  - Tools for easy customization of user interfaces



Dajung Kim, Chanjong Lee, Hosaeng Choi, Jaesuk Ki, Tri-Tech

Sangjin Park, Myungsub Jun, SNU; Chanyoung Lee, KFE

II Demonstration: Virtual KSTAR

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Virtual KSTAR – Different Operation Modes

Real Time Monitoring

- For streaming real time machine operation data
- Real time 3D monitoring of KSTAR machine status

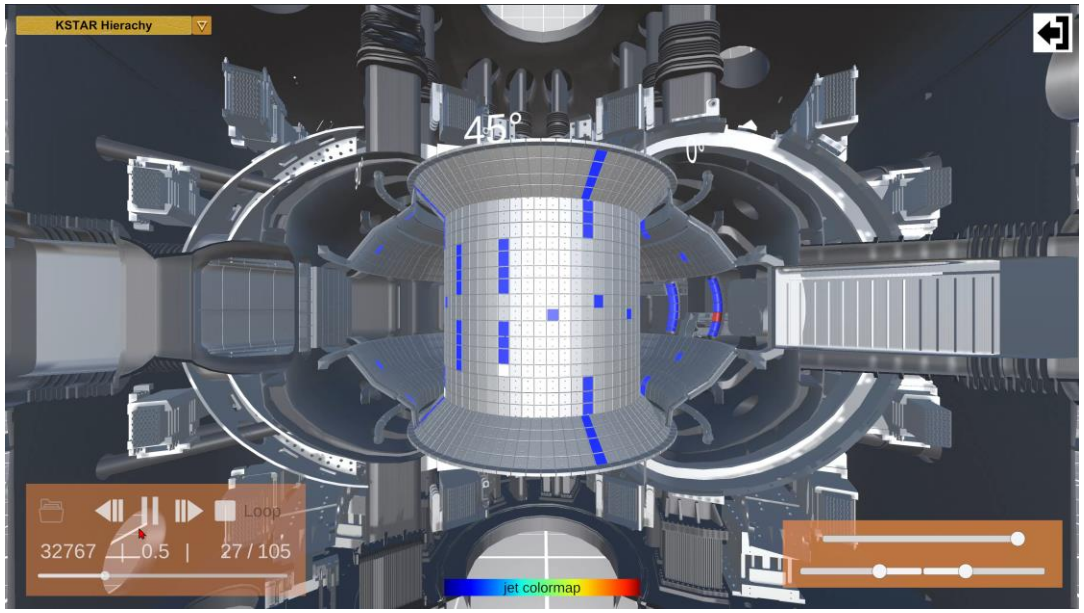
Made with unity

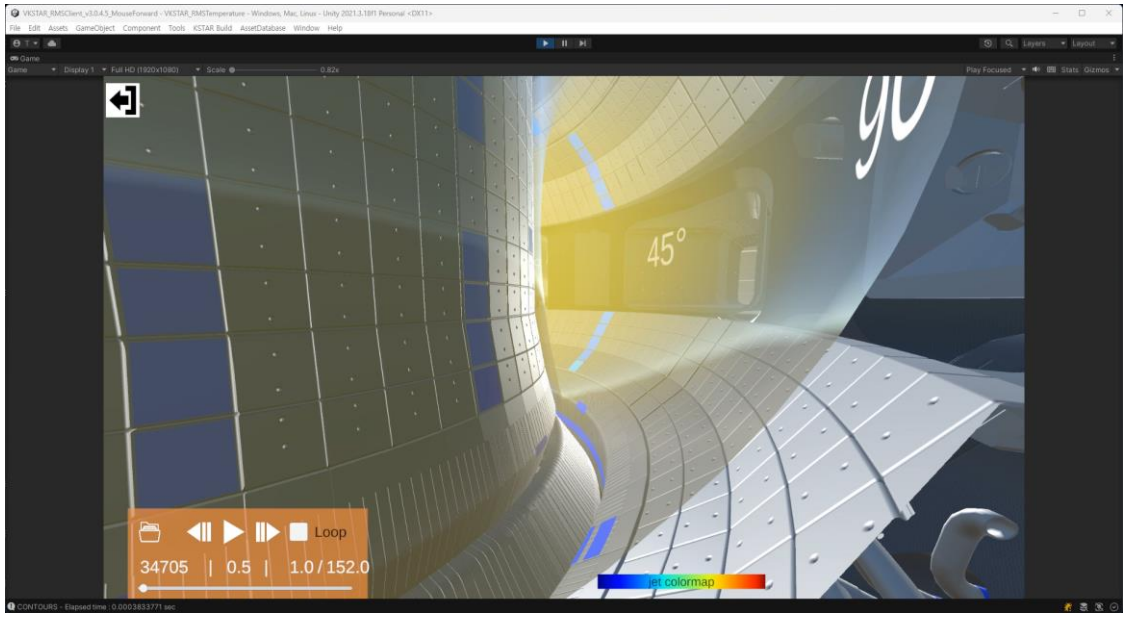
Post-Analysis

- For simulation and diagnostic requiring long processing time
- Integrated visualization and 3D analysis

Virtual KSTAR – Real Time Monitoring

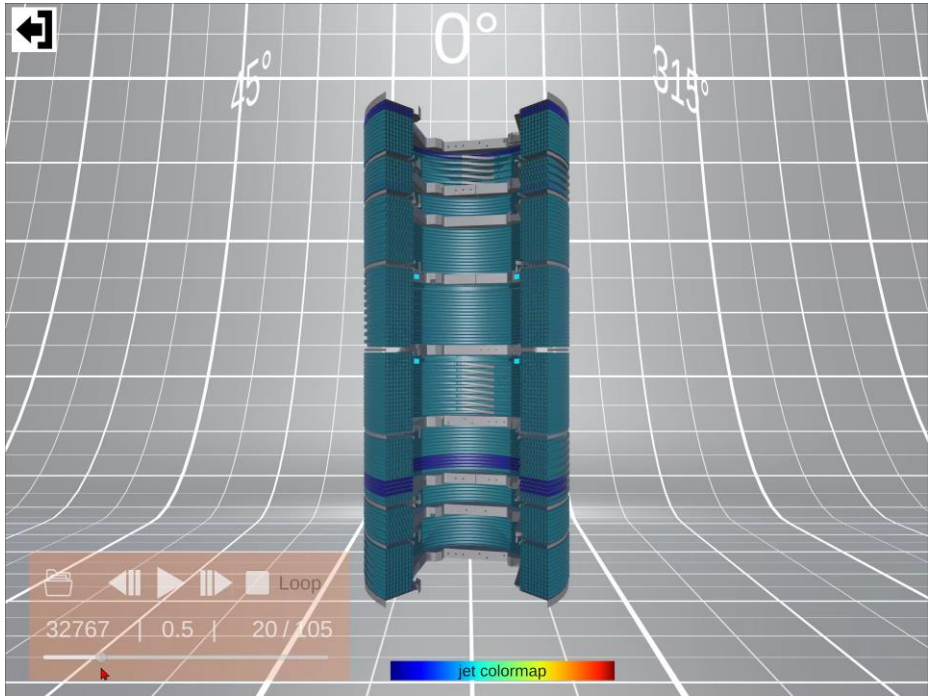
- Real time virtualization of machine operation and plasma status
- Customizable monitoring system
  - Comprehensive monitoring including key machine components & plasma
  - Component specific monitoring e.g. temperatures of plasma facing components

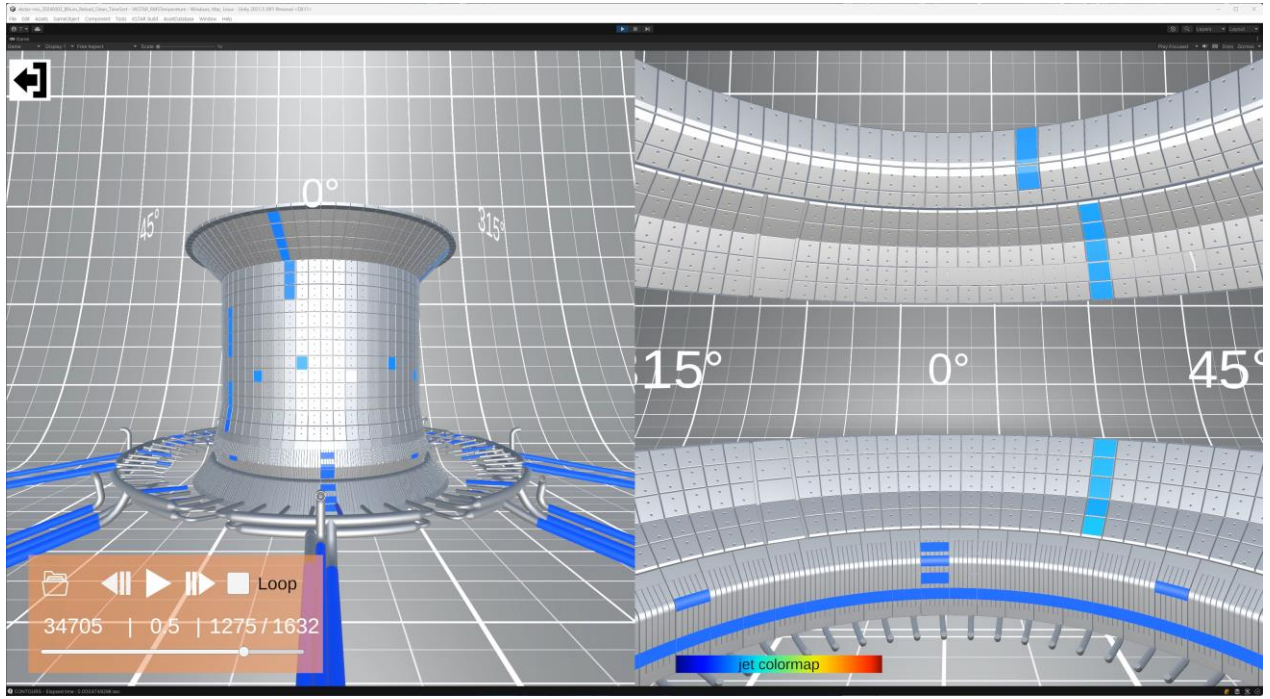




Virtual KSTAR – Real Time Monitoring

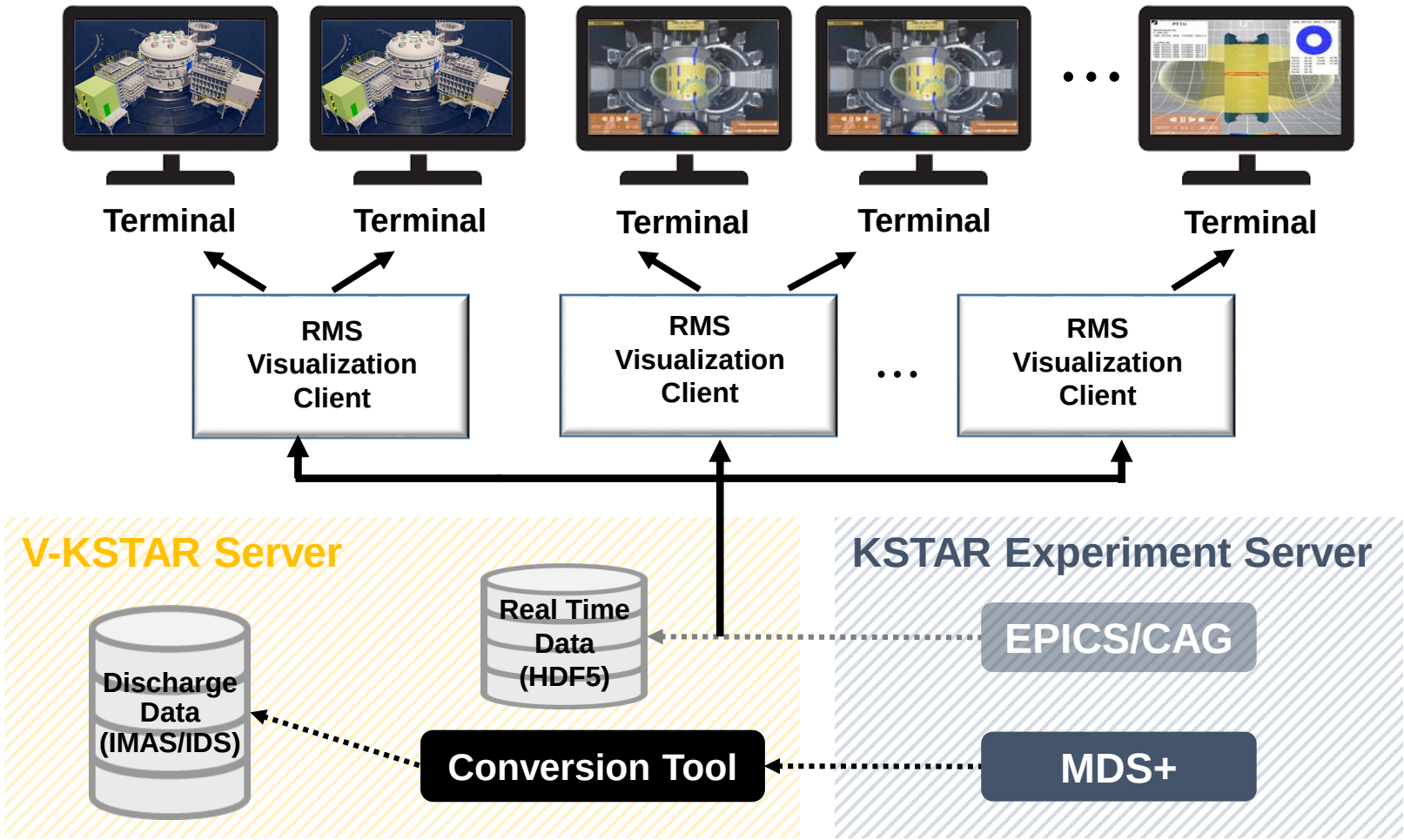
- Real time virtualization of machine operation and plasma status
- Customizable monitoring system – Component specific monitoring





Data Flow for Real-time Monitoring System of Virtual KSTAR

- Real time streaming data is processed to the RMS client of V-KSTAR
- Also, they are converted to HDF5, IMAS/IDS and archived for replay



Virtual KSTAR – Different Operation Modes

Real Time Monitoring

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- Real time 3D monitoring of KSTAR machine status

Post-Analysis

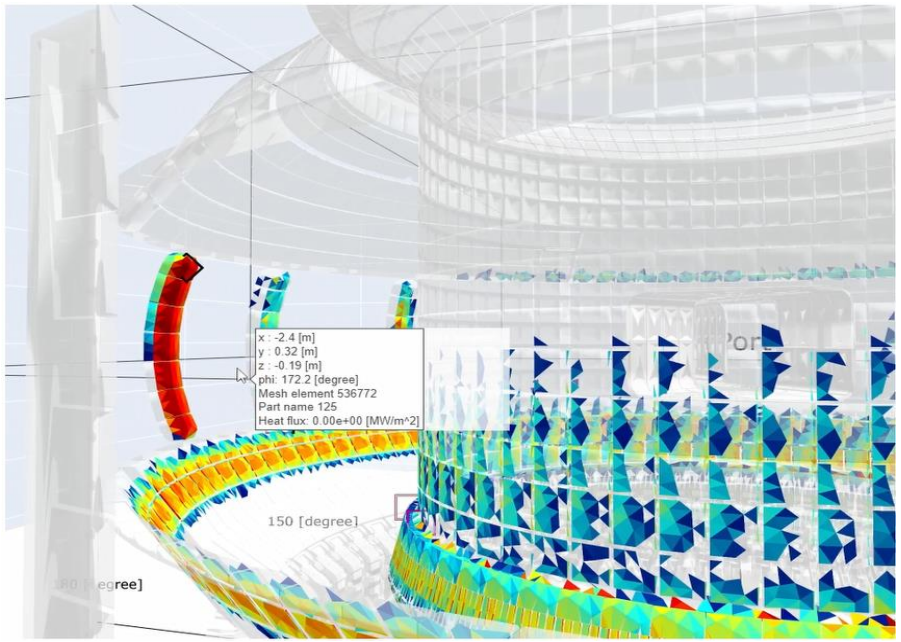
- For simulation and diagnostic requiring long processing time
- Integrated visualization and 3D analysis

3D Fusion Simulation for Digital Twin

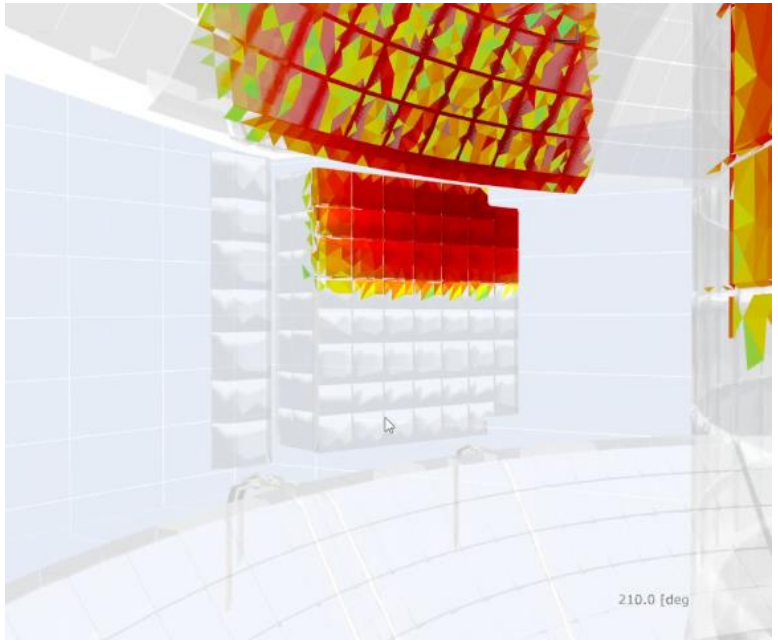
- For digital twin, all existing codes for fusion simulation are useful.
- However, the most useful ones are with full 3D simulation capabilities.
- Unfortunately, many existing codes are with idealized or simplified geometry.
- Different approaches depending on simulation targets and structures of codes:
  - Provide wrapper to add 3D features if code is simple and fast e.g. ECH ray-tracing
  - Modify using the unstructured mesh and 3D analysis libraries e.g. NBI Monte-Carlo
  - Develop new one with new mesh, new 3D algorithms e.g. 3D eddy current

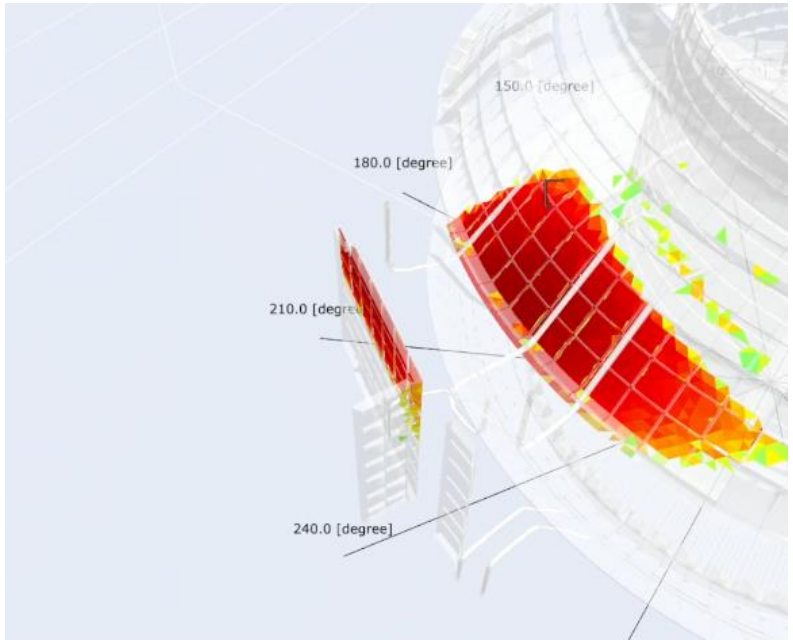
3D NBI Simulation Code for Digital Twin

- NuBDeC: Monte-Carlo particle code for NBI H&CD simulation (T. Rhee, et al Phys. Plasmas 26 (2019) 112504)
- Significantly modified & improved using the 3D mesh and analysis library
  - CAD-based modelling of full 3D in-vessel components of tokamak
  - In addition to conventional NBI H&CD simulation, full 3D modelling of fast ion losses on plasma facing components



Fast ion losses on plasma facing components



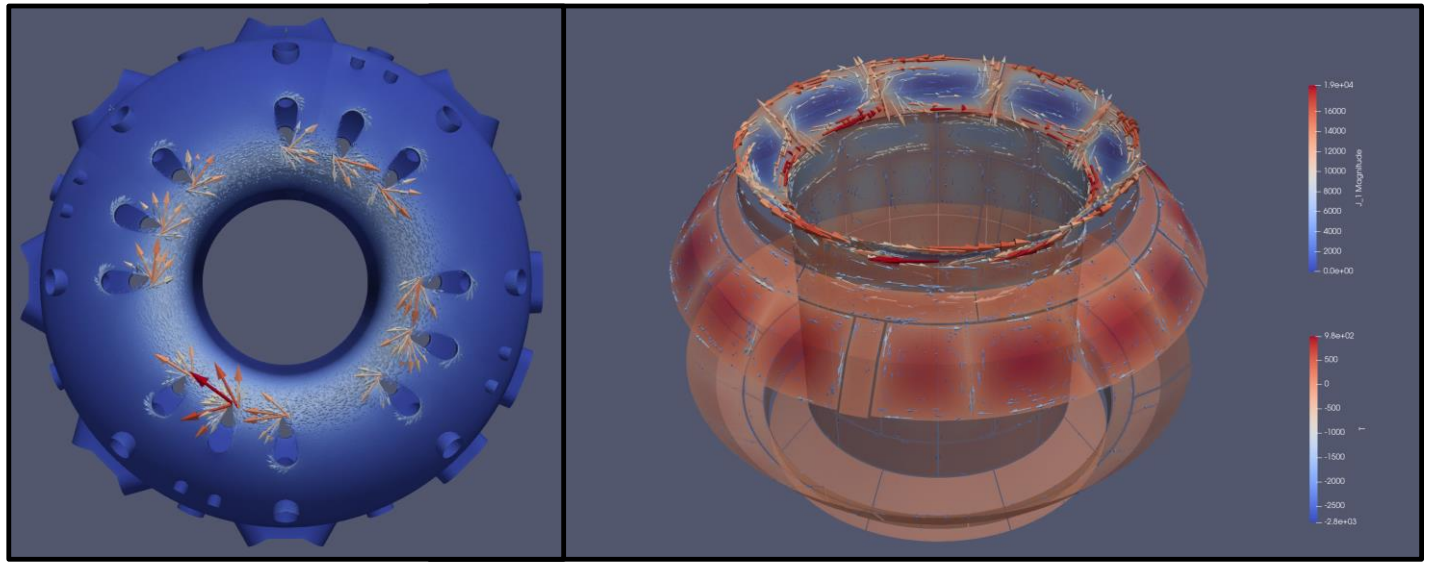


NBI shine-through and heat fluxes on NBI armor and nearby components

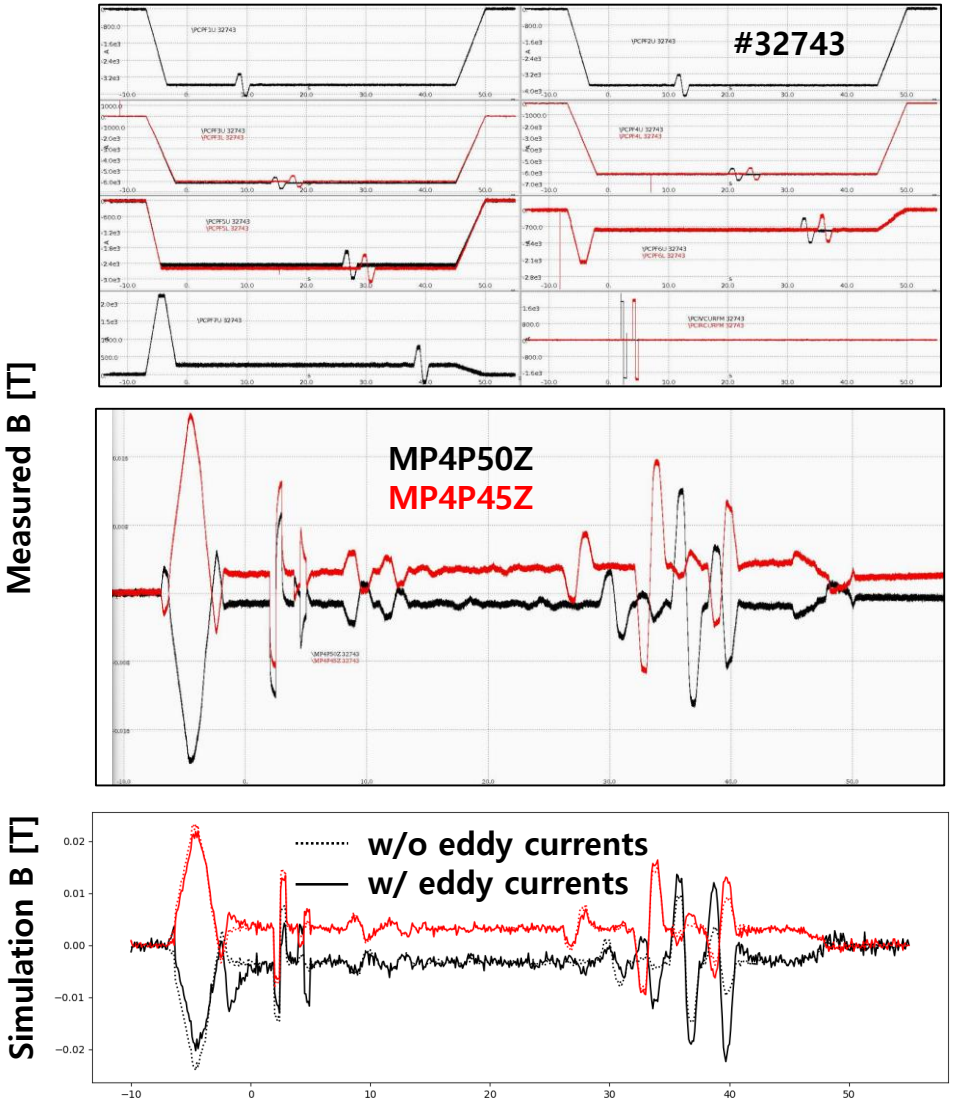
Taewook Moon, Tongnyeol Rhee et al, submitted to Comput. Phys. Commun.
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4537156

3D Vacuum Field & Eddy Current Simulation for Digital Twin

- New code for full 3D calculation of vacuum magnetic field and eddy current, applying fast multi-pole method
- Preliminary Application for KSTAR – Good agreement with MD calibration shots



Eddy currents driven in KSTAR conducting structures



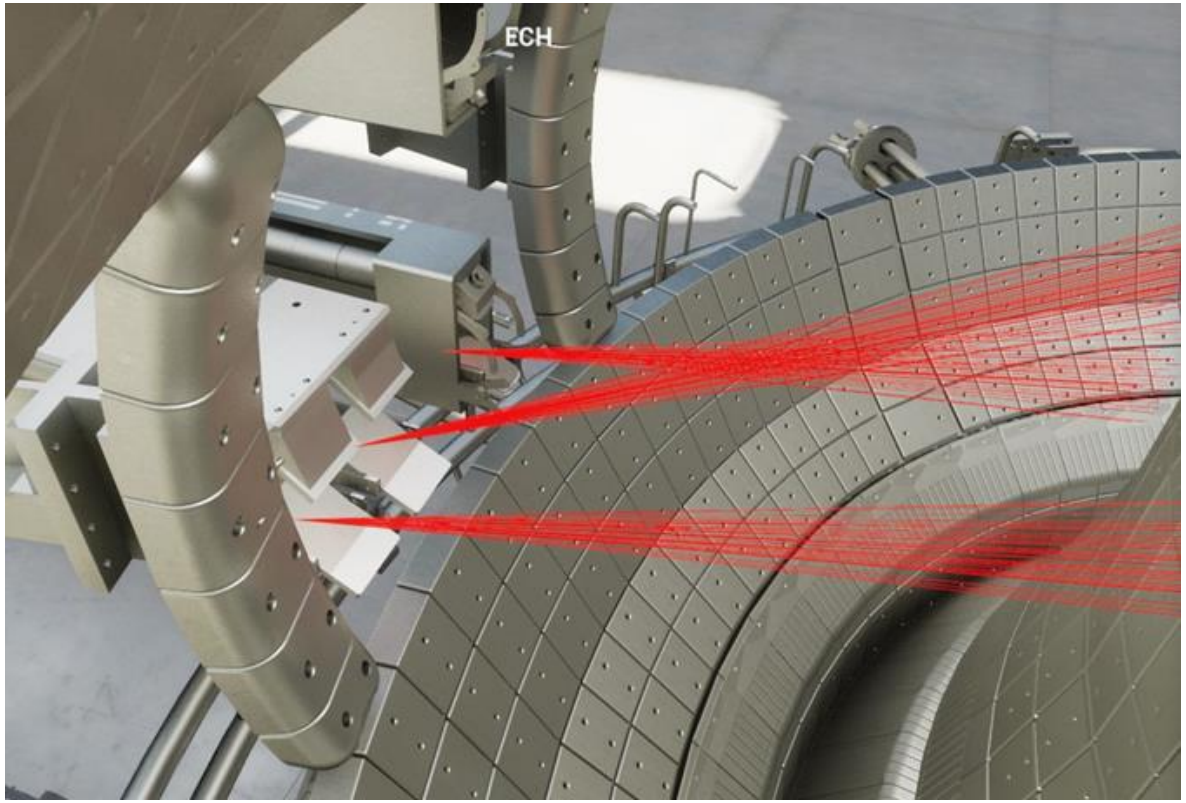
Chanyoung Lee, Gahyung Jo et al, iFPC, Busan, Korea, 2023

Virtual KSTAR – 3D Analysis of NBI Heating

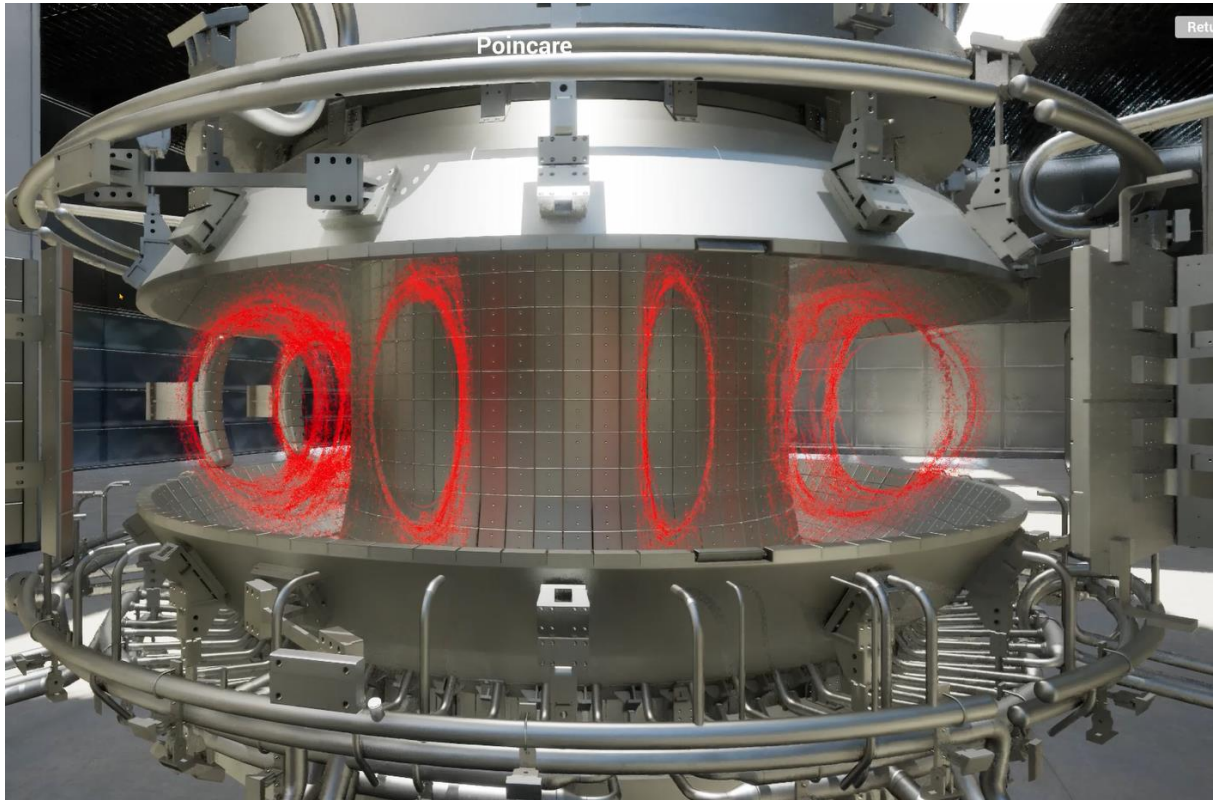
- 3D simulation codes can be integrated into Post-Analysis Mode of Virtual KSTAR

Virtual KSTAR – 3D Analysis of ECH, RMP

- Other 3D simulation codes are being integrated into Virtual KSTAR



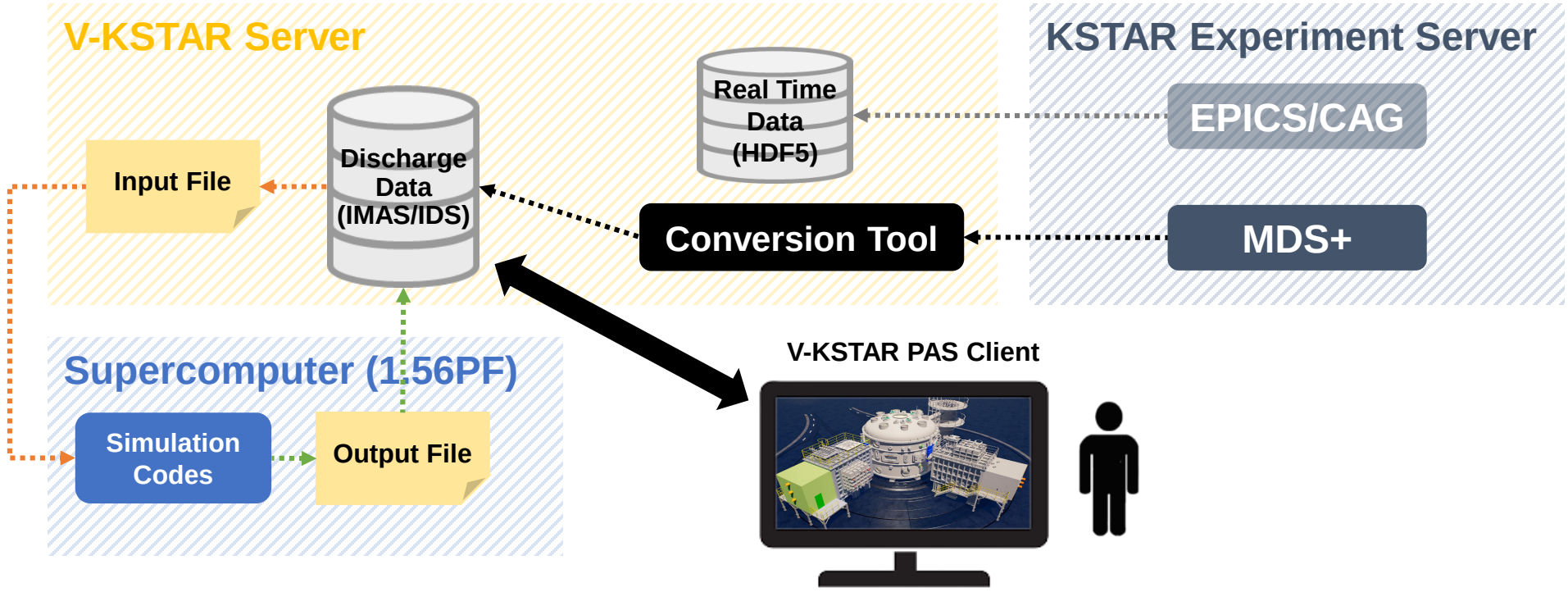
Visualization of ECH ray tracing (TORAY)
(R. Prater et al, Phys. Plasmas 11 (2004) 2349
Minho Woo (KFE), 2021)



Visualization of RMP simulation result from POCA(IPEC)
(Kimin Kim et al, Phys. Plasmas 19 (2012) 082503
Kimin Kim et al, Phys. Plasmas 24 (2017) 052506)

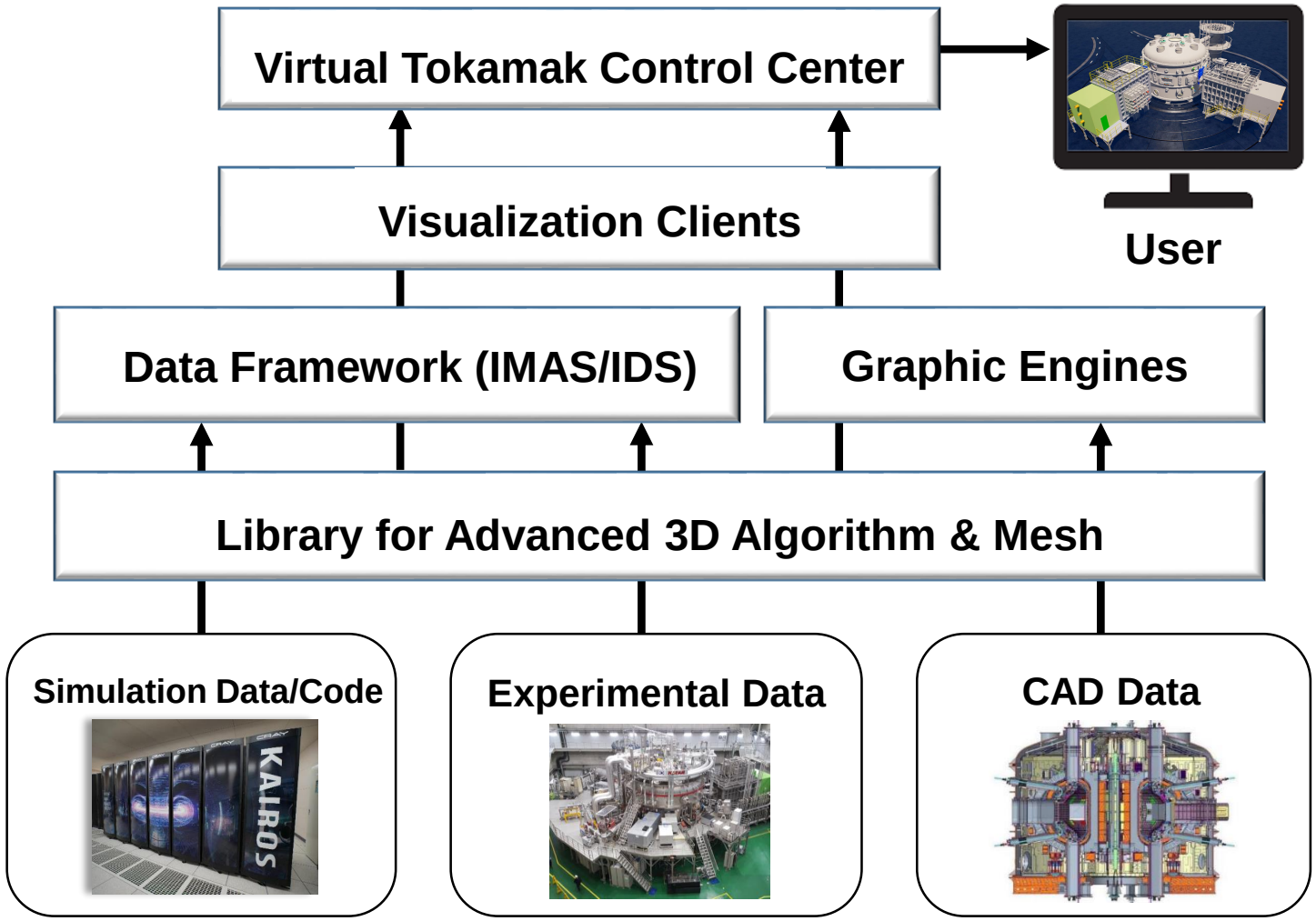
Data Flow for Post-Analysis System of Virtual KSTAR

- Experimental data are converted to and stored as IMAS/IDS.
- Some are passed to V-KSTAR client directly, and some others are converted to simulation input.



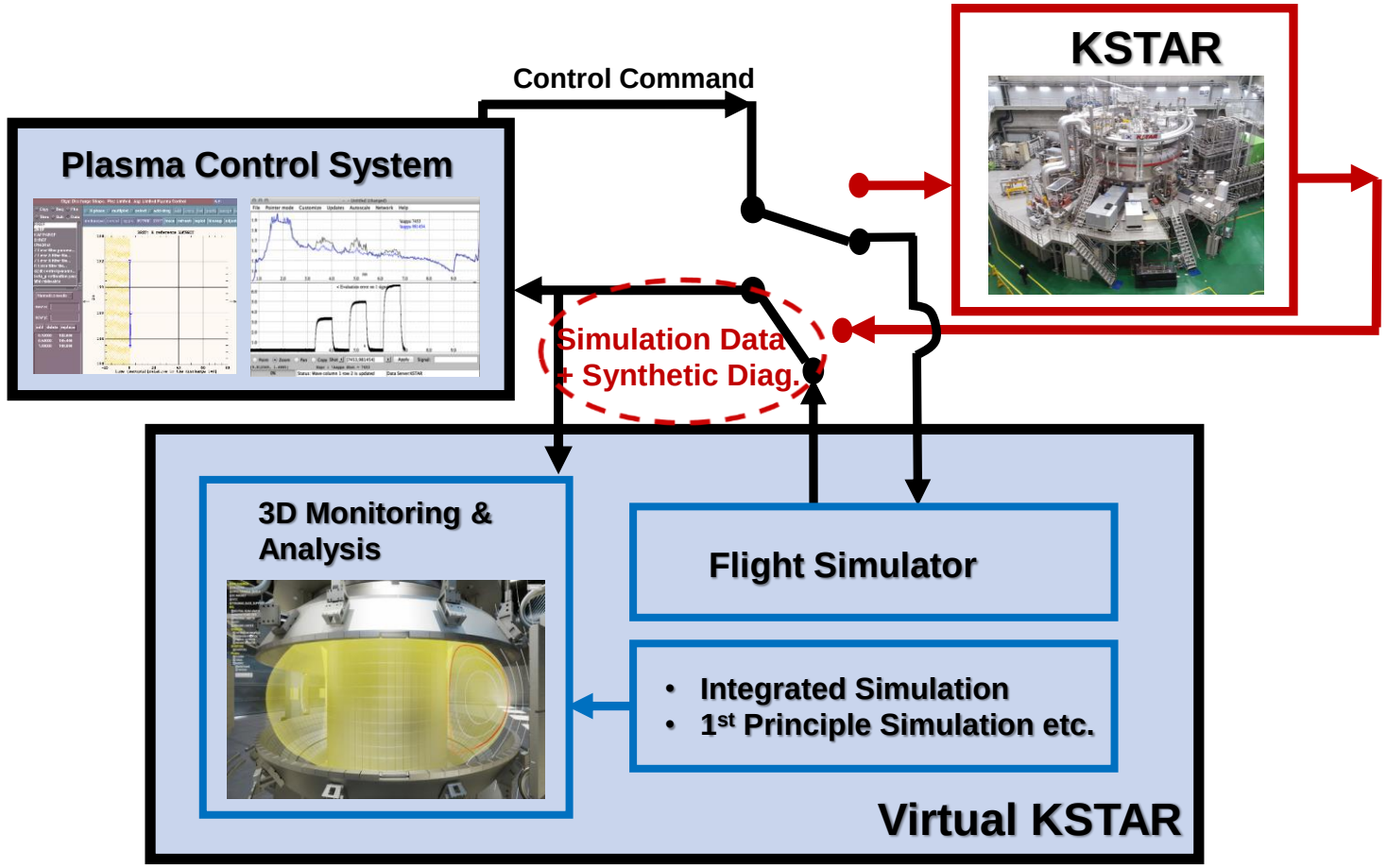
Summary

- Key enabling elements derived for digital twin technology
  - Parallelizable unstructured mesh, algorithms for 3D analysis, graphic SW based on game engines etc.
- Development of virtual tokamak platform for
  - Real time monitoring of machine operation and experiment
  - 3D fusion simulation & analysis



Future Direction

- 3D simulation platform for diagnostic development, synthetic diagnostics.
- Incorporation of plasma control simulation for virtual experiment.
- Various AI-related developments for faster and more user interactive simulation.
- Highly welcome international collaboration !!!



Thank You for Attention !