Virtual Tokamak for Integrated Physics and Engineering Analysis

Chanyoung Lee

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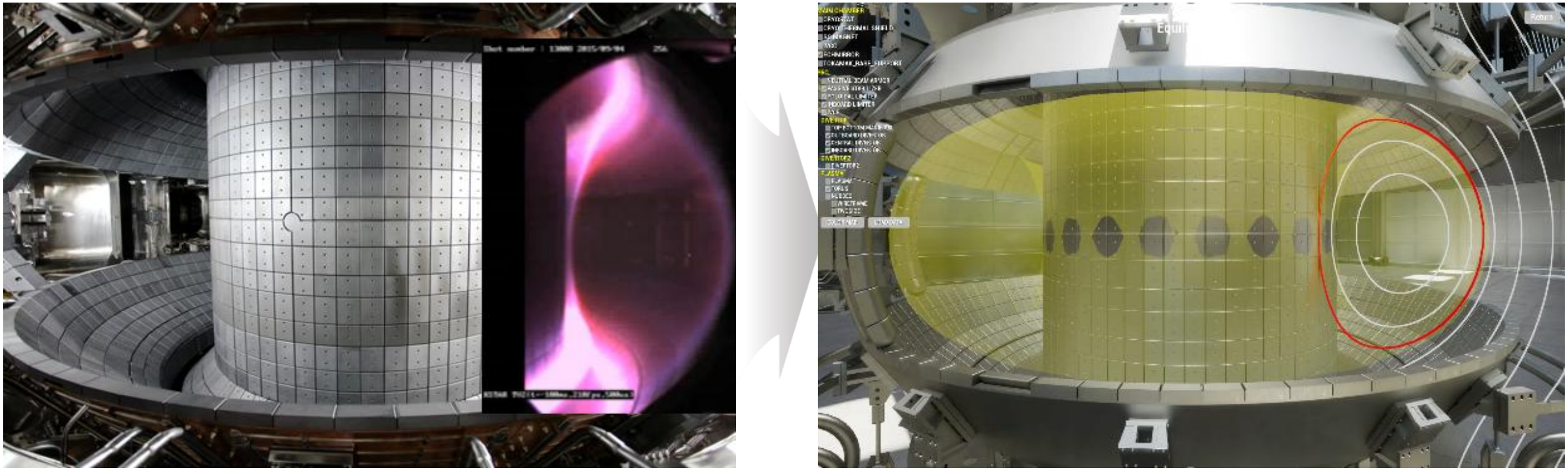
IAEA Workshop on Digital Innovation for Fusion Research
Dec. 9-12, 2025

Introduction & Motivation

- Digital twin technology → a bridge between physics and engineering for fusion R&D
- Implementation of Virtual KSTAR and its limitation
  - Necessity to develop digital twin platform, which can generalize the functions of Virtual KSTAR



Implementation of Virtual KSTAR by combining KSTAR CAD, experiment, simulation data

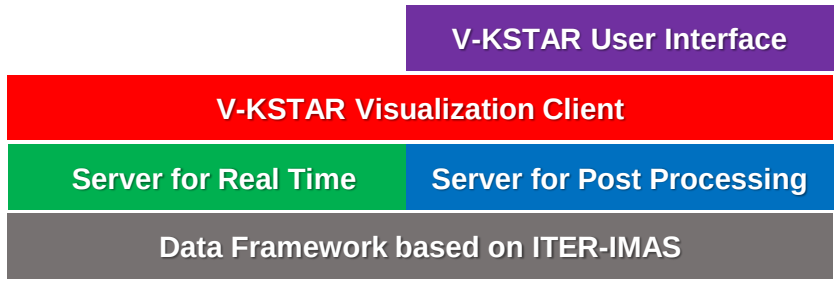
Jae-Min Kwon et al, Fusion Eng. Des. 184, 113281 (2022)
Jae-Min Kwon et al, IEEE Trans. Plasma Sci. 52, 3910 (2024)

Contents

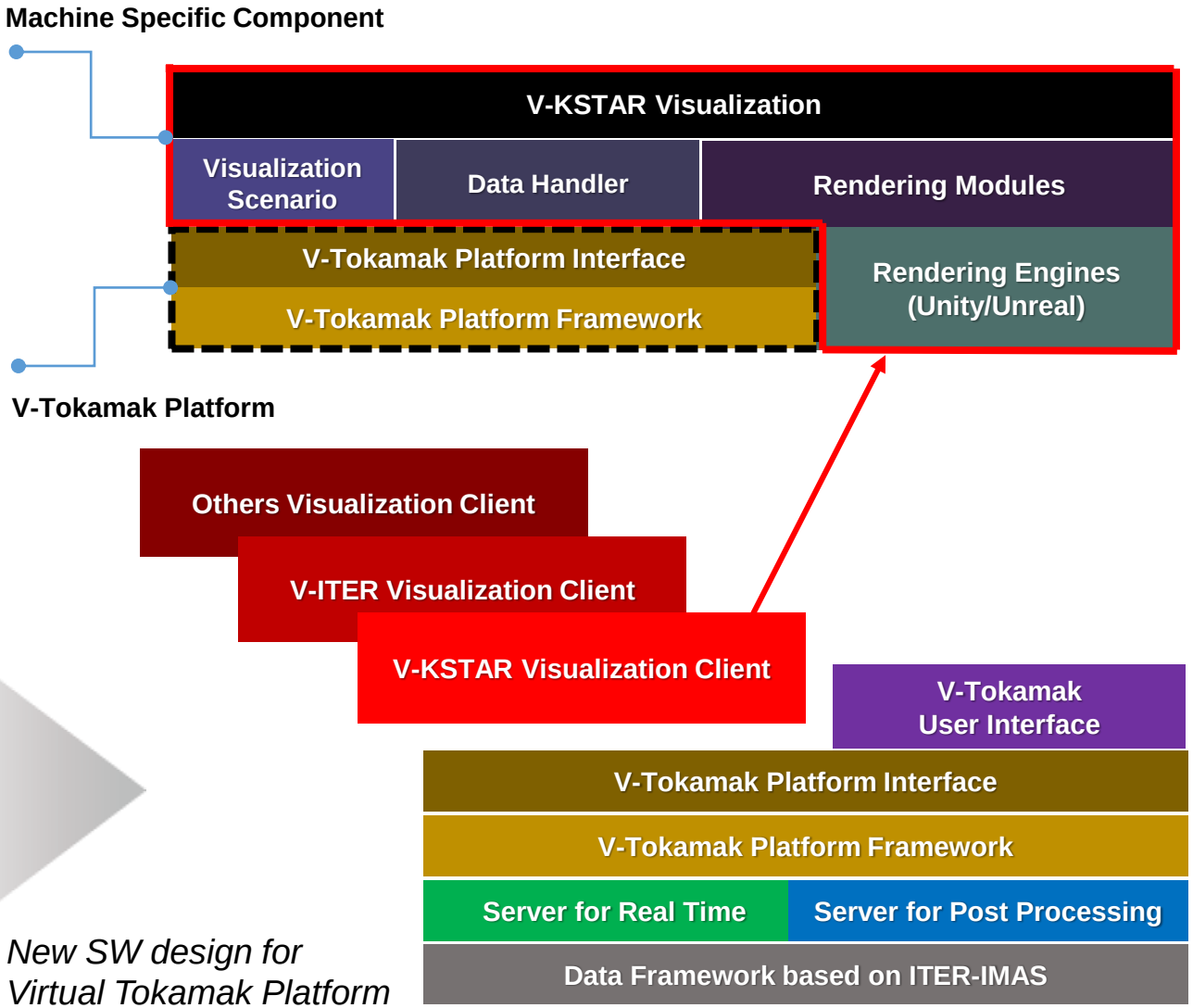
Virtual Tokamak Platform
— WILL

Virtual Tokamak Platform – WILL

- Original V-KSTAR → many KSTAR-specific features and dependences.
- **WILL** (**V**ersatile **V**irtual platform for **I**ntegrated fusion simu**L**ation and ana**L**ysis)
  - Inherits most of enabling SW and technologies for original V-KSTAR, and refactors them for better modularization and abstraction
  - Key SW components: mesh, data framework, libraries for 3D data analysis, graphic engines etc.



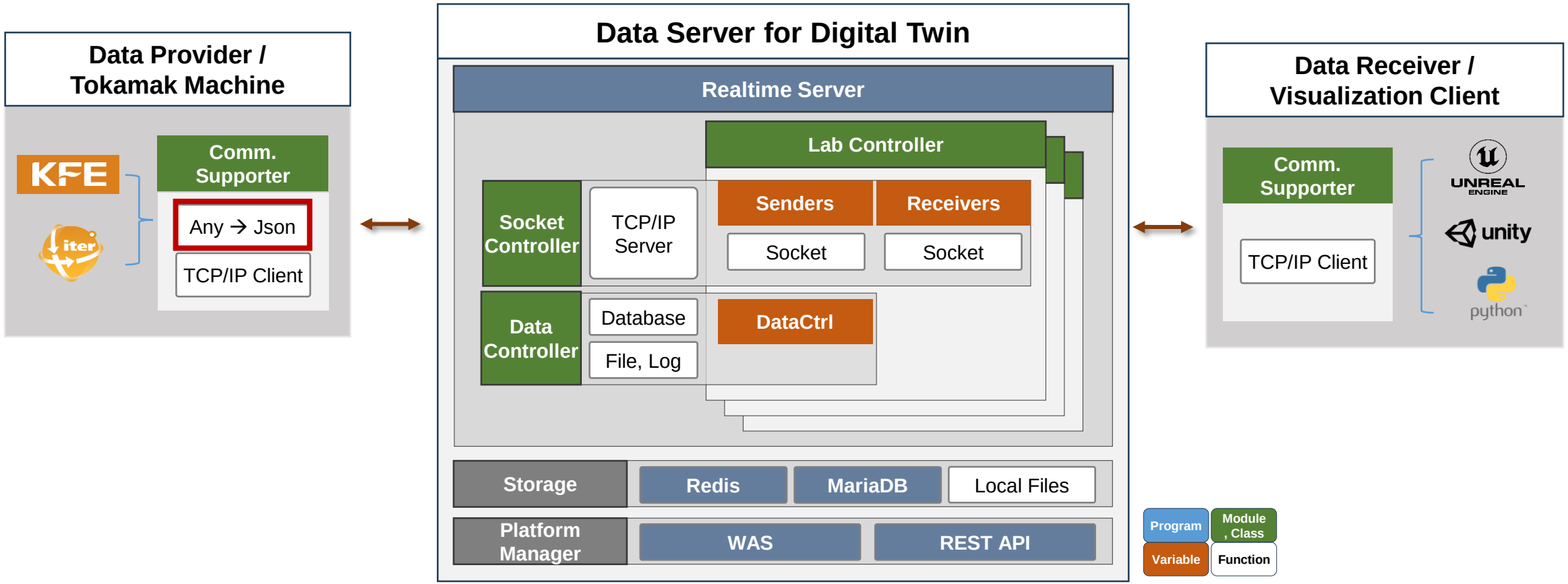
Old SW design for Virtual KSTAR



New SW design for Virtual Tokamak Platform

WILL – Data Framework

- Necessity to deal with variety of data formats (legacy ones, codes with their own standards etc.)
- ITER-IMAS/HDF5 and JSON → format standardization with flexibility to handle variety of inputs.



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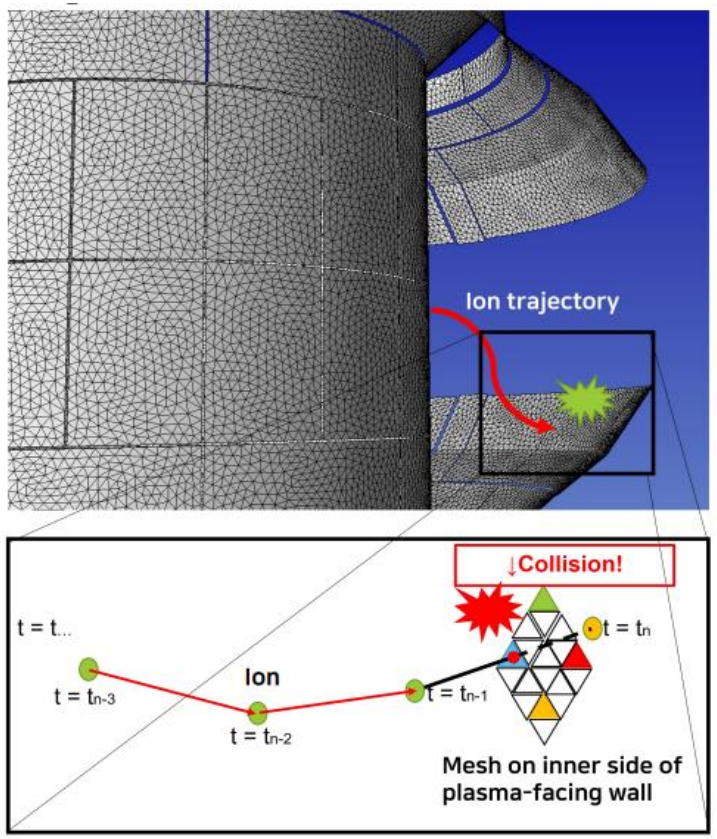
WILL – Advanced 3D Data Analysis

PUMI (Parallel Unstructured Mesh Infrastructure, SCOREC)



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, RF-rays, beams for diagnostics
- 2-phased collision detection: 1) broad phase to narrow down and 2) narrow phase to pinpoint down
- Being developed as general C++ libraries
- Facilitate the developments of various 3D simulation & analysis codes for fusion R&D.

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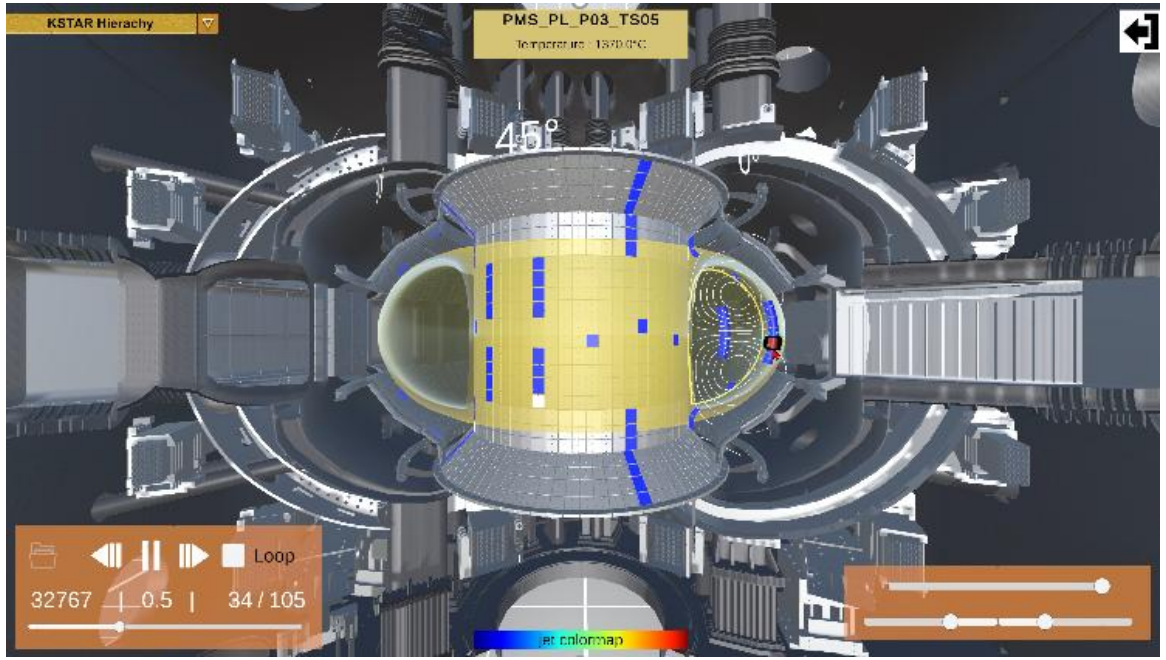
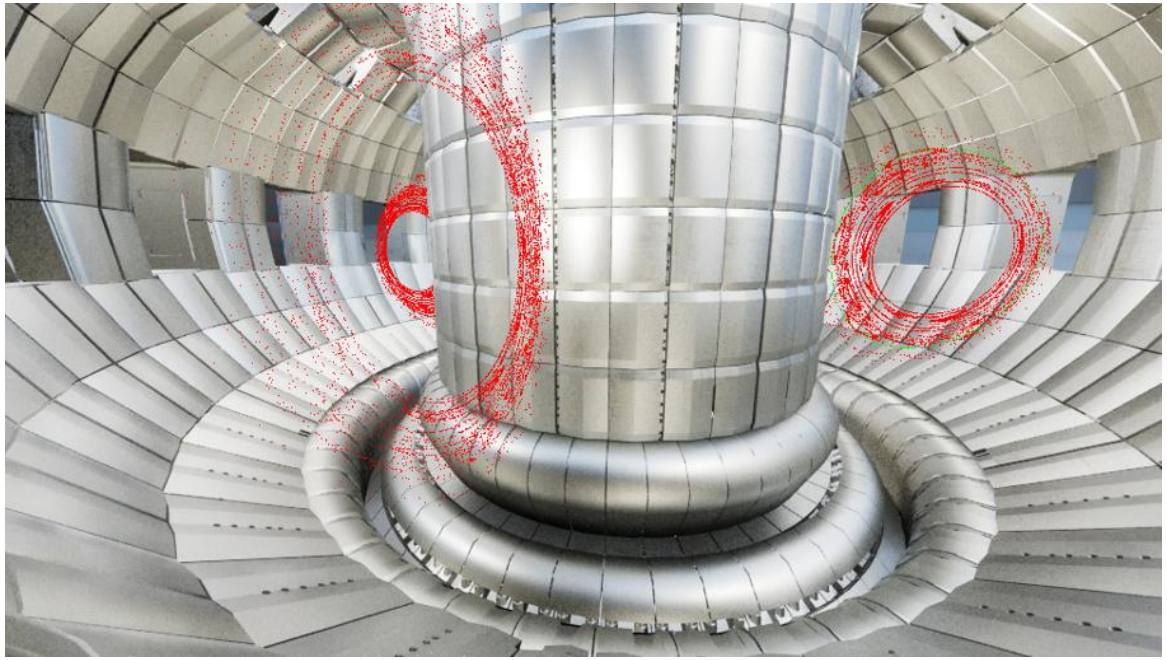
Fusion and Plasma application research Laboratory

Taeuk Moon, Eisung Yoon, Comput. Phys. Commun. 309, 109490 (2025)

WILL – Visualization using Game Graphic Engines

- Employ two graphic engines for game development





Made with unity

- Application for real time processing
- Suitable for laptop, mobile device

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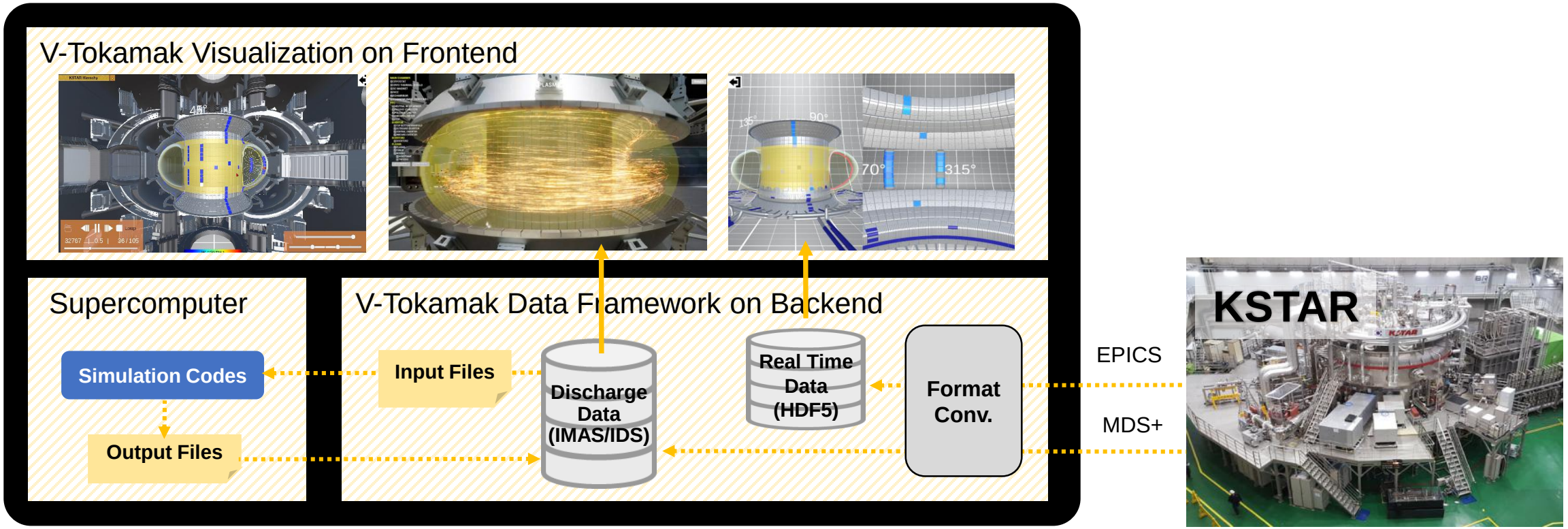
- Application for time consuming analysis, simulation etc.
- Require powerful computing resource

WILL – Overall Structure

- A collection of SW's connecting operating tokamak device with dedicated computing resource
- Enable virtualization of arbitrary tokamak according to user's needs



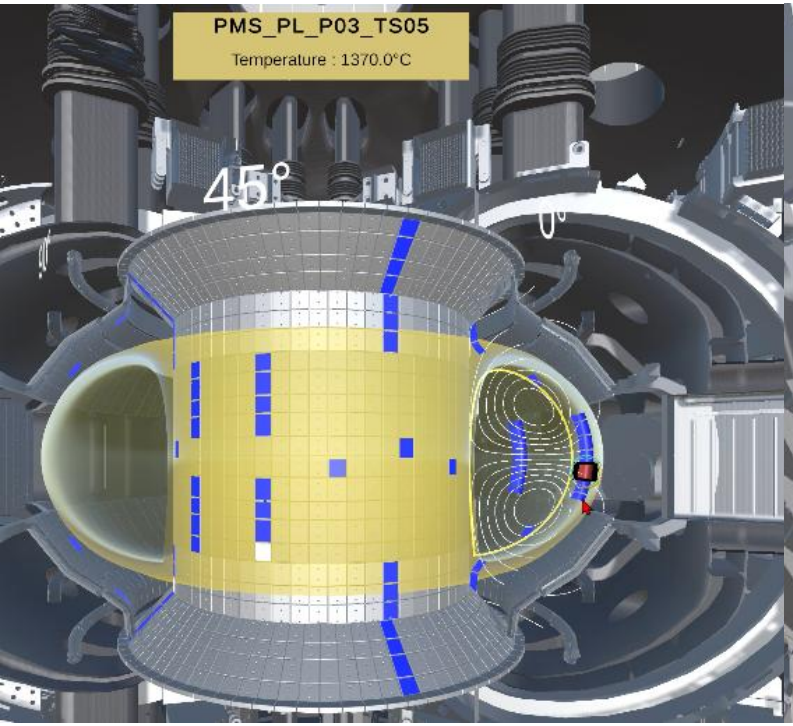
Jae-Min Kwon et al, Fusion Eng. Des. 184, 113281 (2022)
Jae-Min Kwon et al, IEEE Trans. Plasma Sci. 52, 3910 (2024)

II

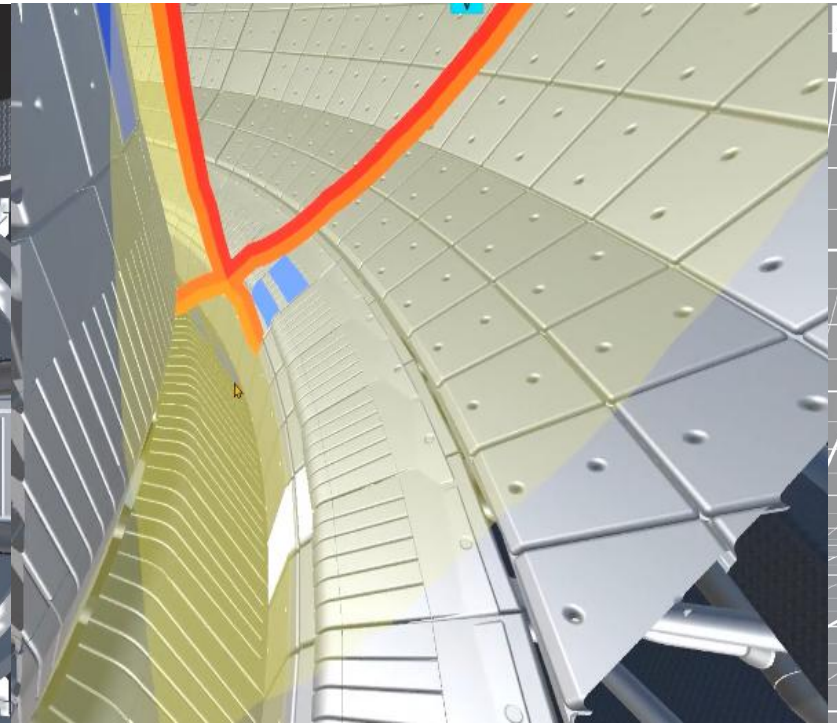
Application – Virtual KSTAR & Virtual ITER

Real Time Monitoring of Tokamak Experiment

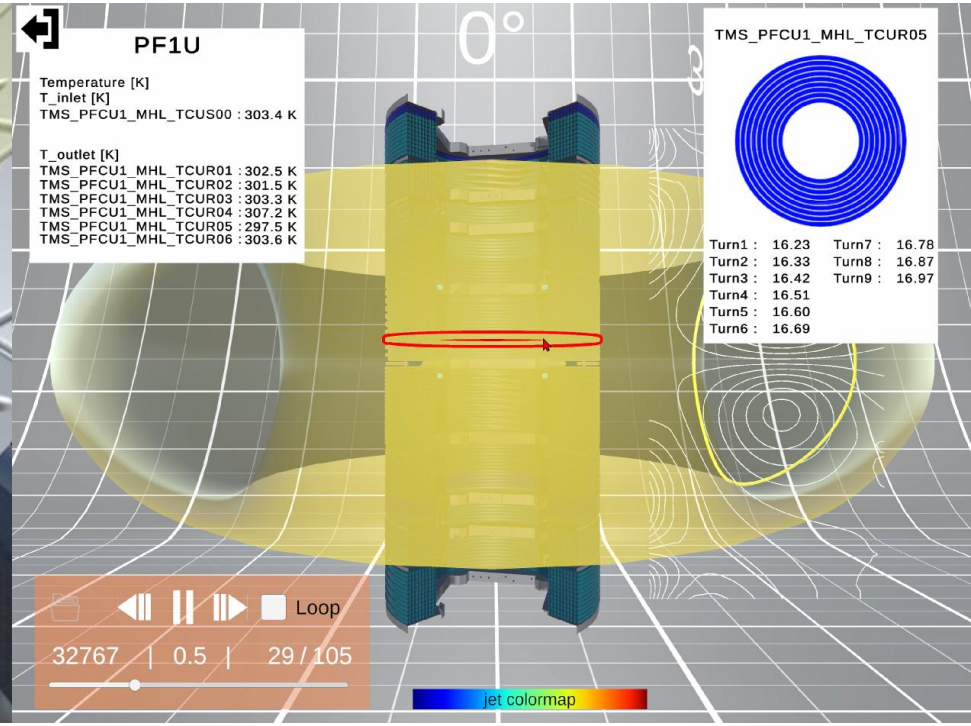
- Various operational info (e.g. first wall temperatures, real time EFIT) can be visualized in real time
- Easily customizable according to user's needs



Temperature Distributions on Plasma Facing Components



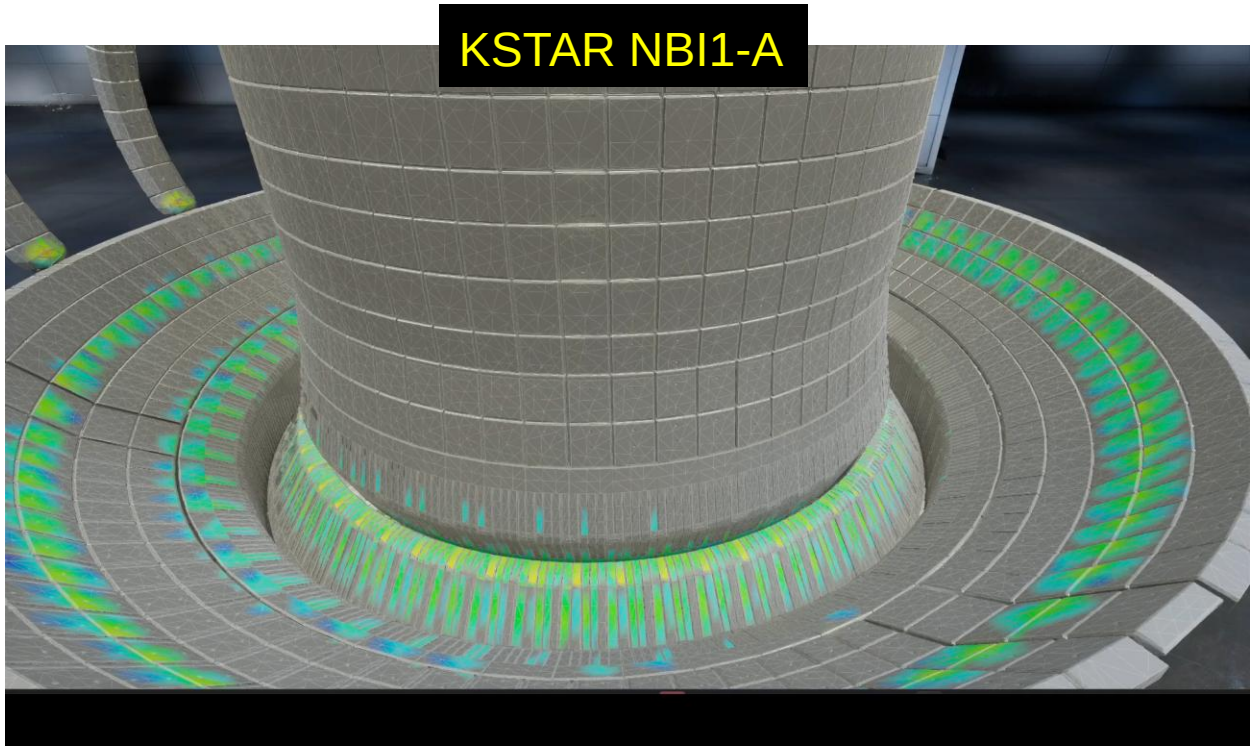
Real Time Plasma Equilibrium with X-points and Divertor Striking Points

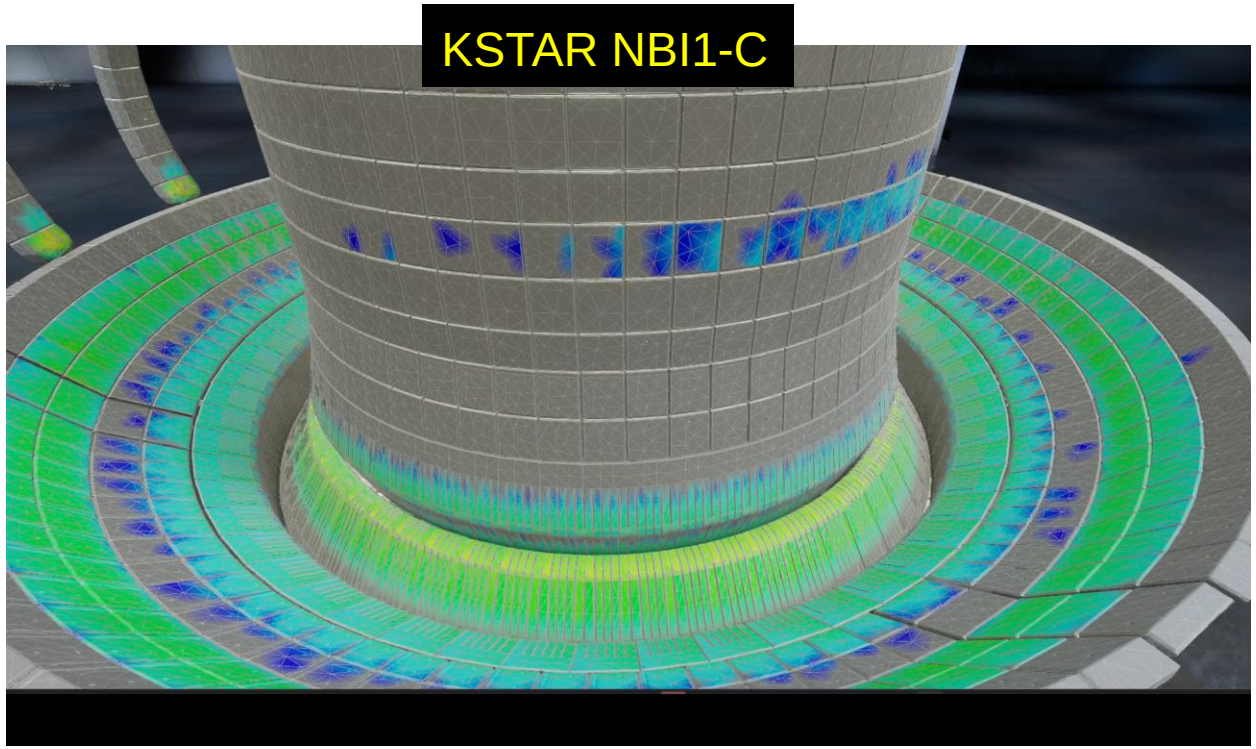


Plasma Equilibrium and CS Coil Operation Information e.g. helium temperature on each turn

Full 3D Simulation and Analysis – NBI

- Monte-Carlo simulation of NBI fast ion losses on plasma facing components with 3D effects (e.g. leading edge)
- In KSTAR, different NBI ion sources result in notable differences in fast ion loss patterns

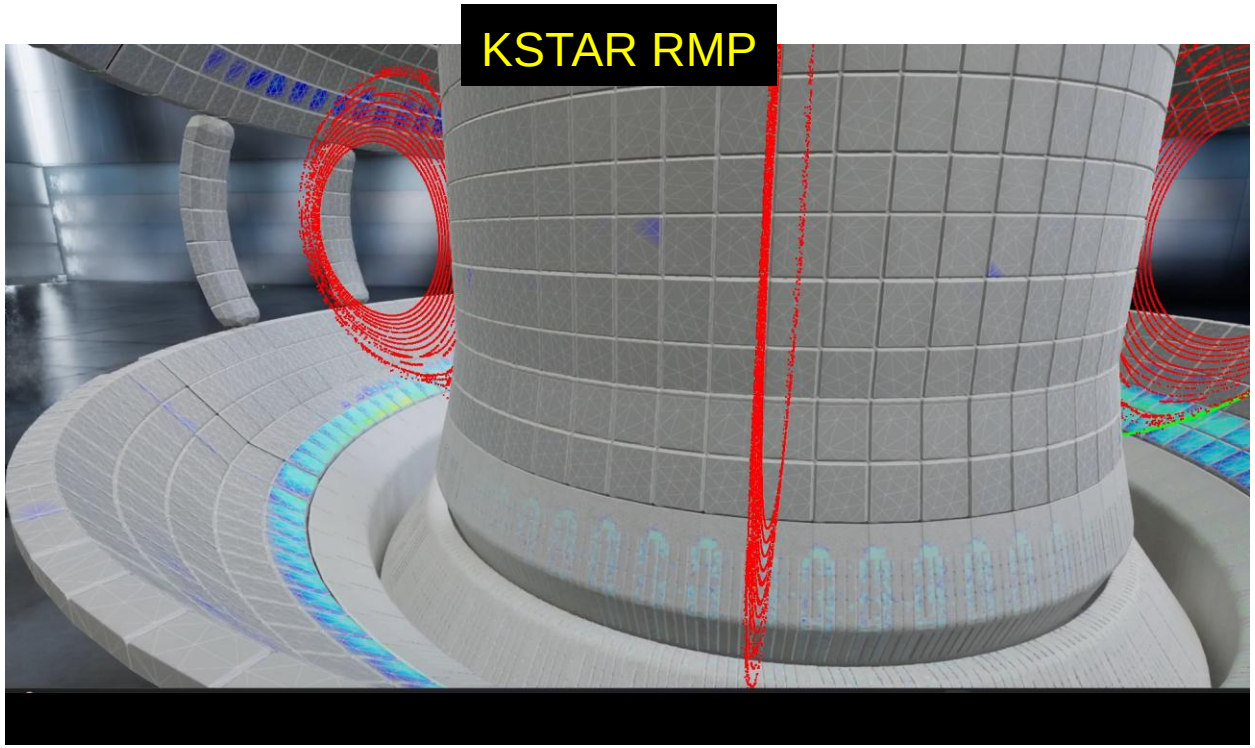


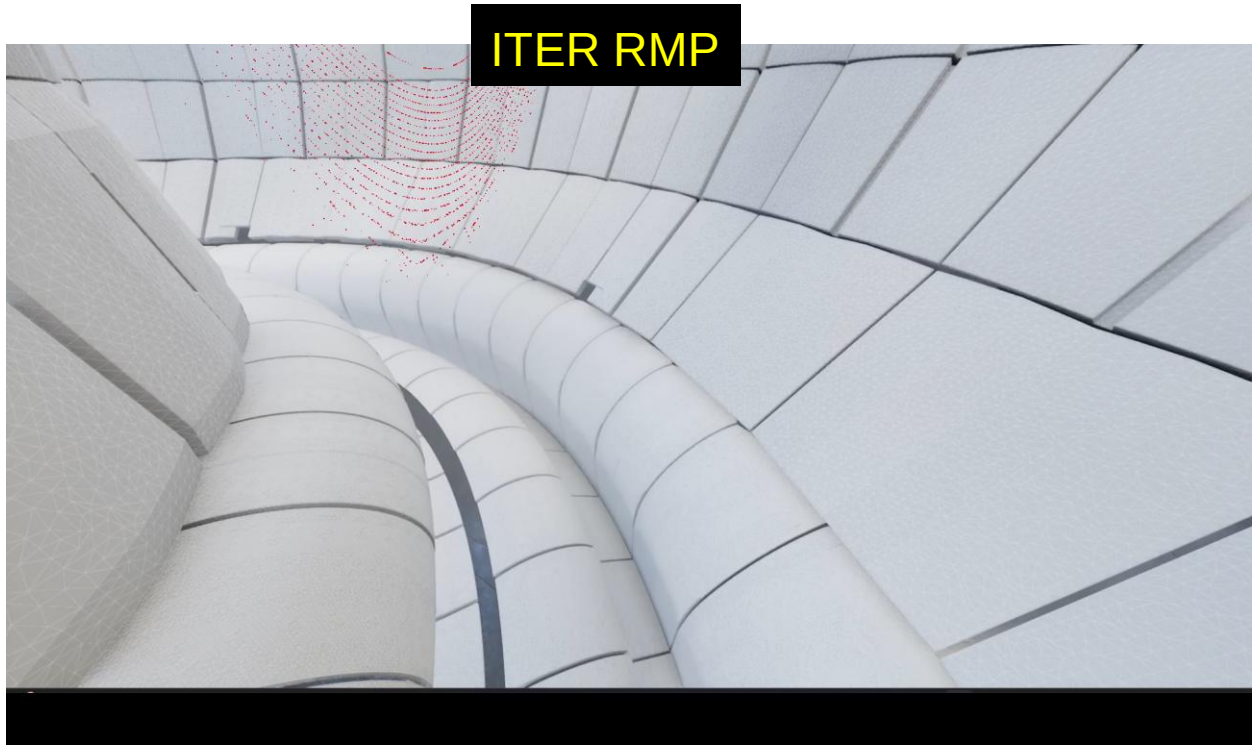


Taeuk Moon, Eisung Yoon, Comput. Phys. Commun. 309, 109490 (2025); IAEA FEC 2025;

Full 3D Simulation and Analysis – Resonant Magnetic Field Perturbation

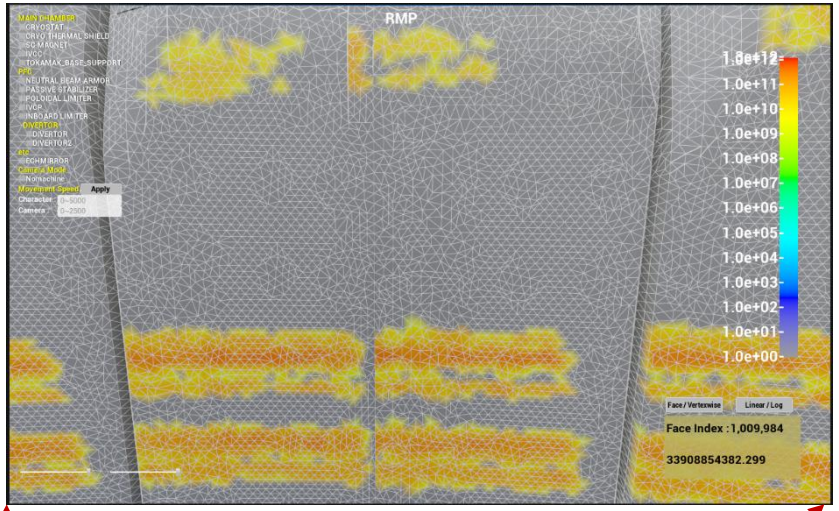
- Full 3D simulation and analysis of resonant magnetic field perturbation(RMP)-induced heat flux pattern changes, their impacts on plasma facing components

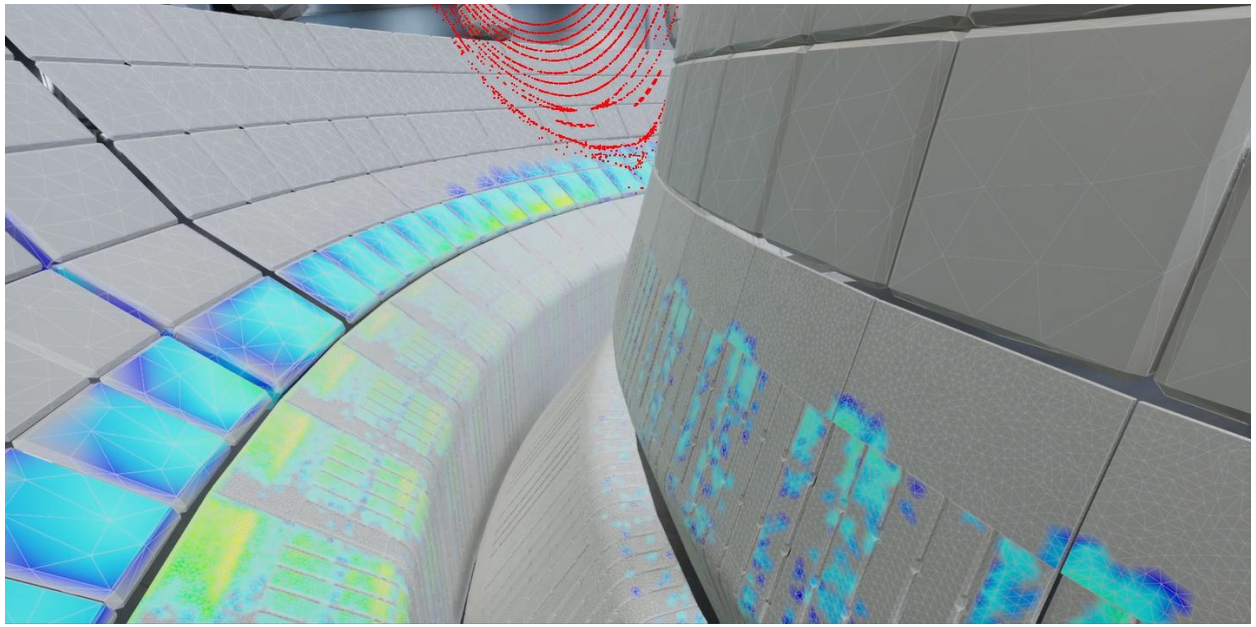


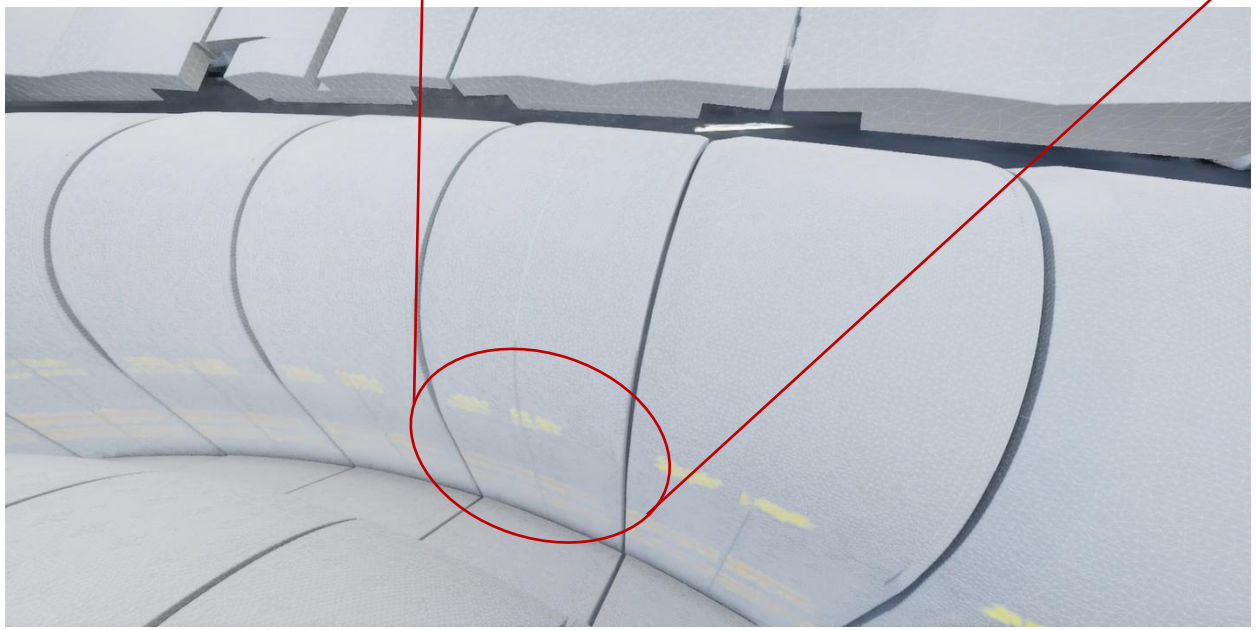


Full 3D Simulation and Analysis – Resonant Magnetic Field Perturbation

- Different mesh resolutions for more effective simulation and analysis: 5mm for KSTAR (2M meshes), 12mm for ITER (5M meshes). Also different resolutions for different components.
- Significantly different patterns from KSTAR and ITER

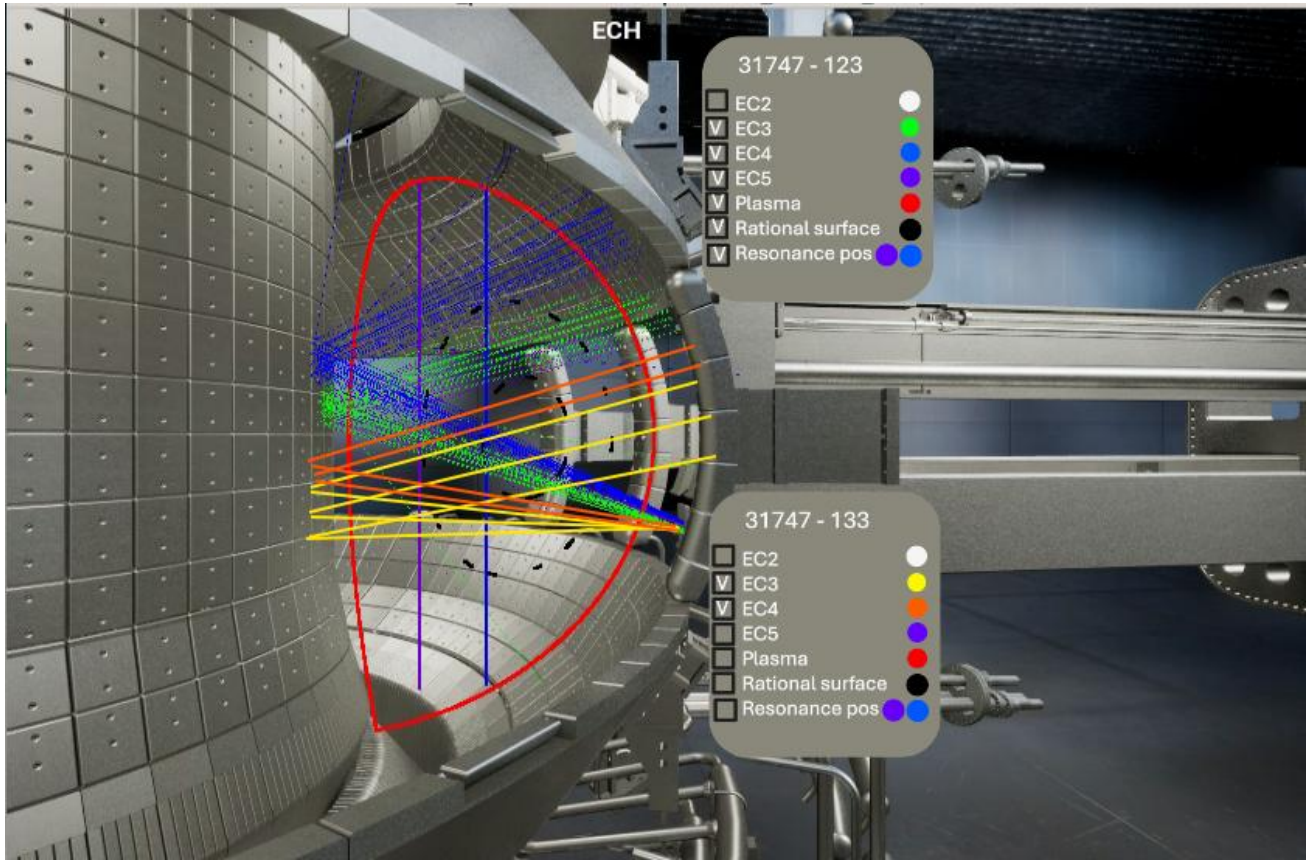




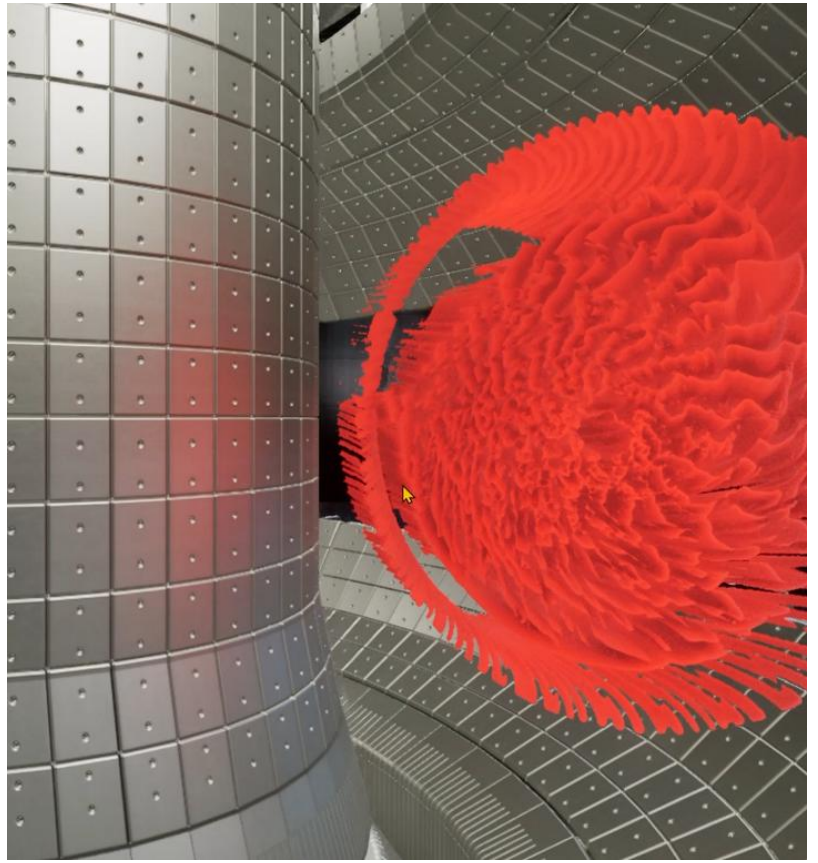


Full 3D Simulation and Analysis – ECH, Gyrokinetic

- ECH ray-tracing along with information on resonance, reflection, and potential hot spots, with comparison for different ECH configurations
- 3D turbulence structures extracted from global gyrokinetic simulation

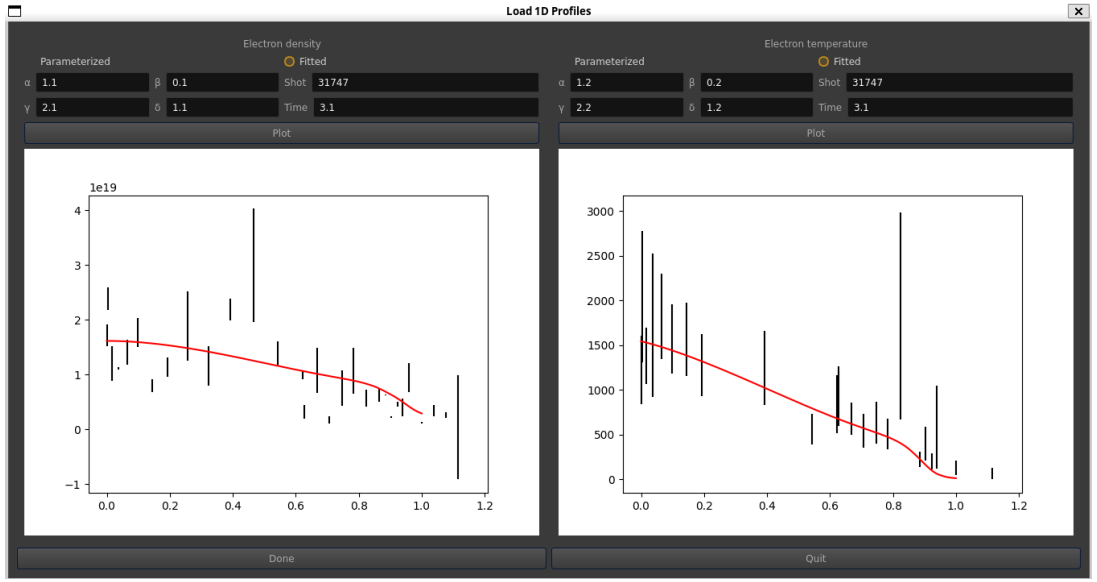


TORAY ECH ray-tracing with RF resonance, reflection info

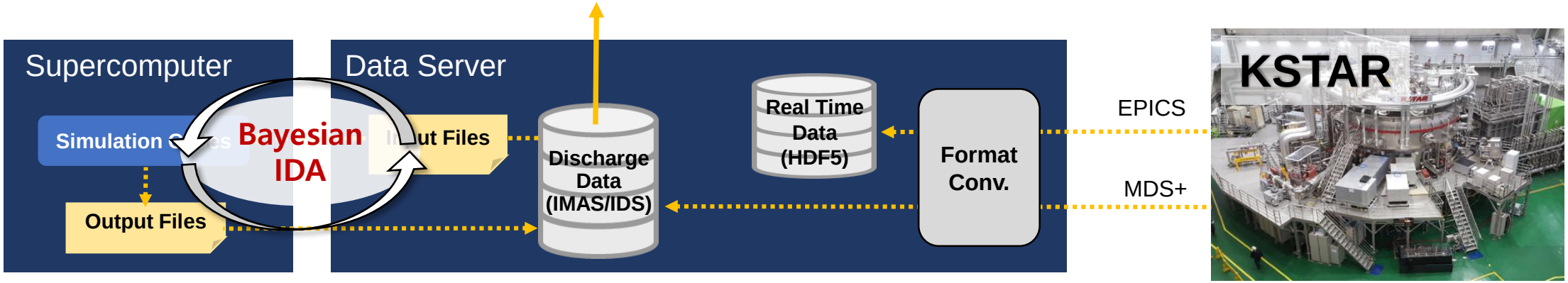


Turbulent density contours from global gyrokinetic simulation

Bayesian IDA based Between Shot Analysis



- Bayesian Integrated Data Analysis was implemented for robust profile reconstruction.
- TRANSP analysis was automated.
- ML-surrogates are being developed, which will be integrated into the IDA and TRANSP analysis loop for faster and more interactive between shot analysis.



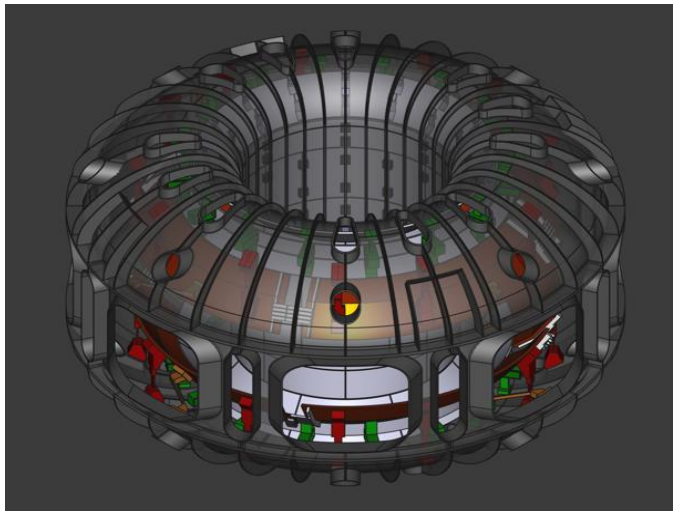
Chanyoung Lee, Jaewook Kim, Laurent Terzolo, Jaekil Lee, KFE

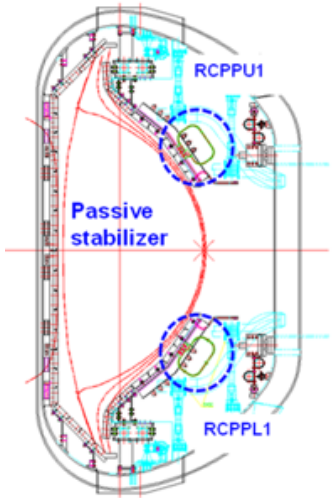
III

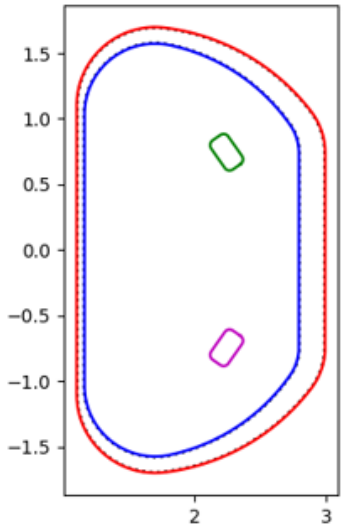
On-going Works & Future Direction

Integration On-Going – Full 3D Eddy Current Simulation

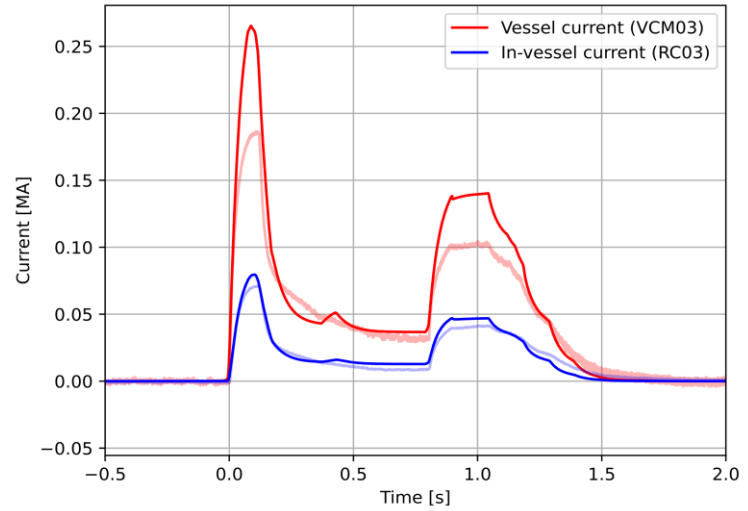
- Advanced mathematical algorithms
  - Volumetric mesh discretization of full 3D model
  - Differential geometric FEM combined with fast multipole and hierarchical matrix
- Vacuum magnetic fields and eddy currents are in good agreement with KSTAR measurements
- On-going work to implement simplified plasma model for VDE analysis

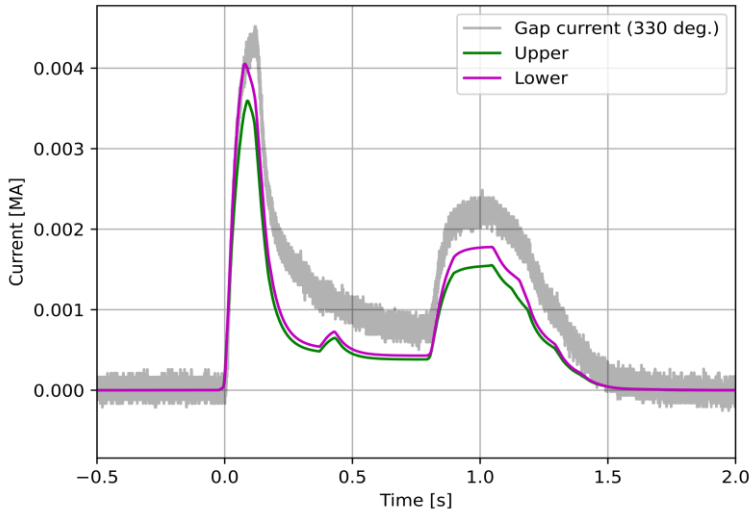






Full 3D model of KSTAR in-vessel conducting structures (left), and Rogowski coils for eddy current measurements (middle, right)



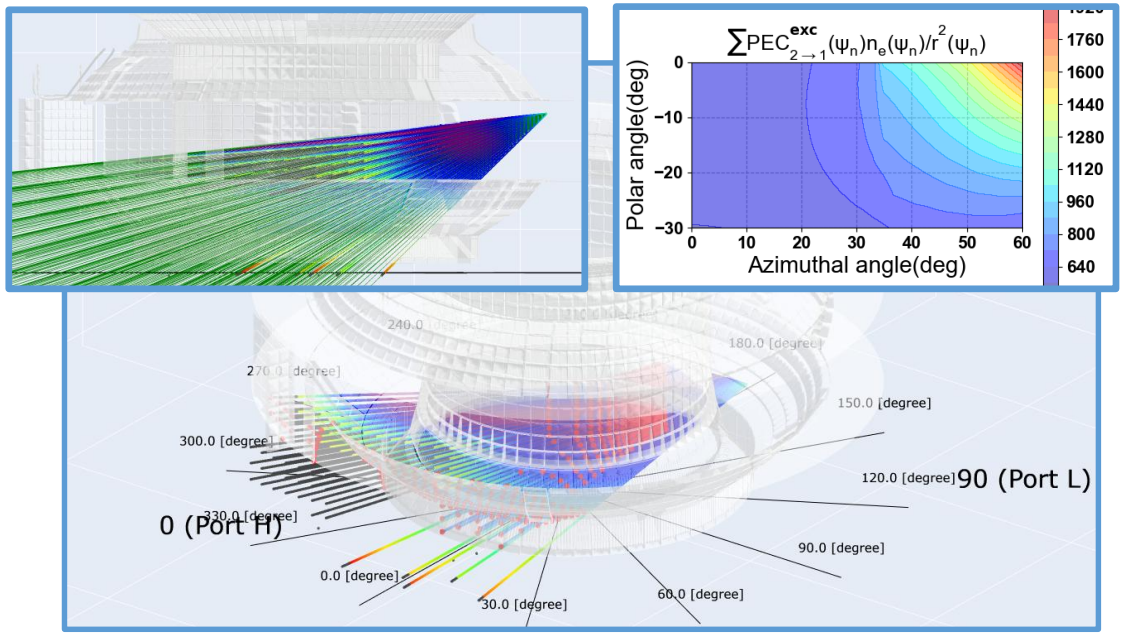


Comparison of measured (shaded) and calculated(solid) eddy currents

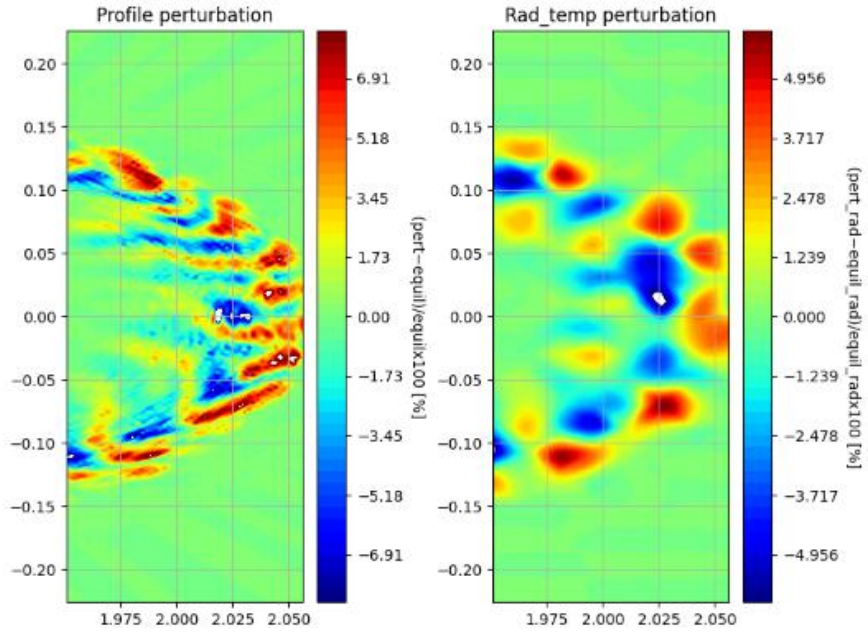
Chanyoung Lee et al, Comput. Phys. Commun. 317, 109864 (2025)

Integration On-Going – Synthetic Diagnostics

- Employing unstructured mesh and 3D data analysis algorithms, full 3D interactions of particles and beams can be calculated and recorded very efficiently
- A new full 3D code was developed to design the new Ly-α diagnostics for neutral particles on KSTAR
- Other synthetic diagnostic codes are also being developed (e.g. ECEI)



Beam tracing for line-of-sight modeling and calculation of expected Ly-α signal
(Jaesuk Lee, Taeuk Moon, K.-C. Lee, Y.-c. Ghim, KAIST, KFE, iFPC2025)

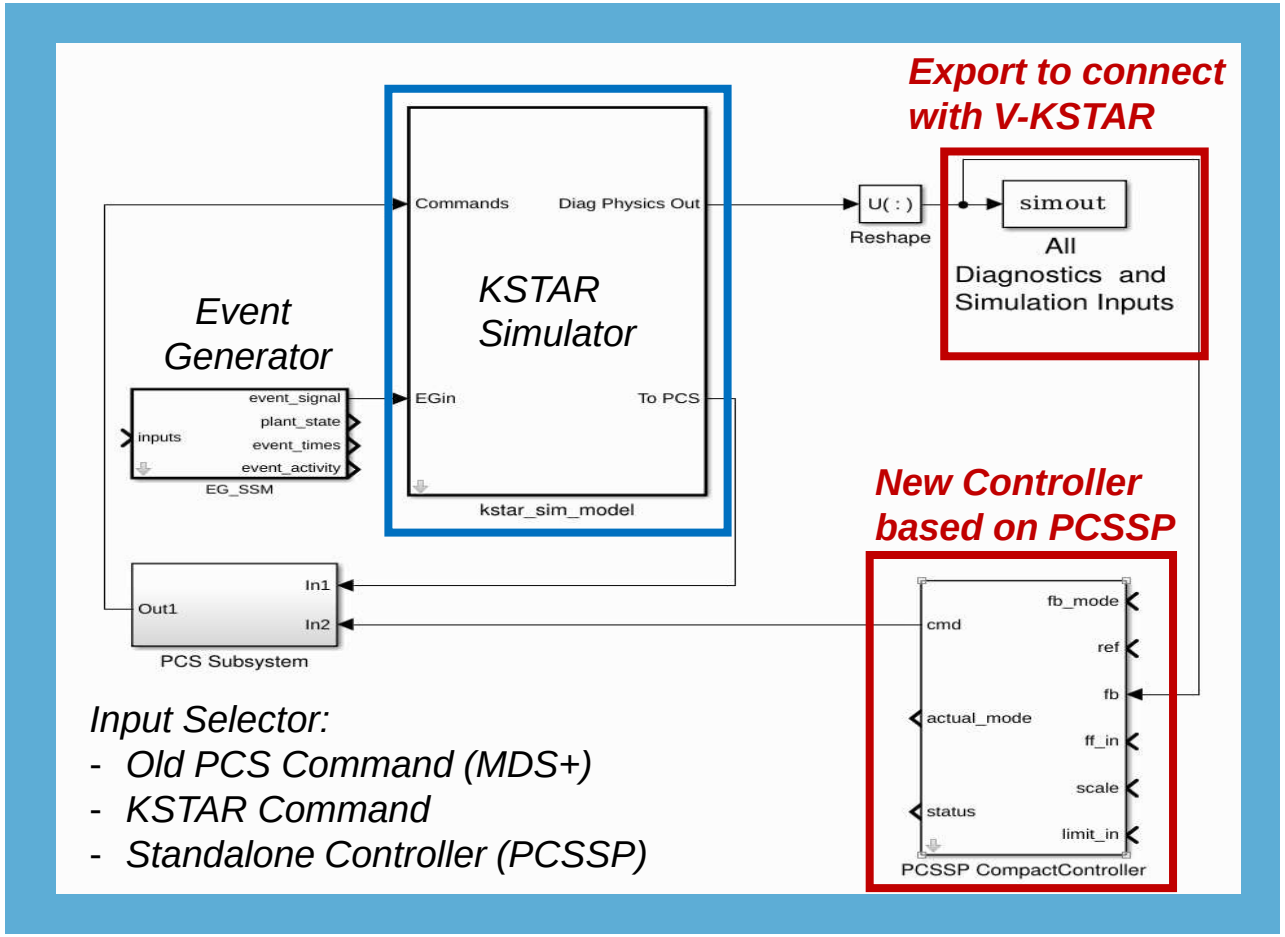


Synthetic ECEI diagnostics on GK turbulence simulation data
(Taeyoung Ahn, Sumin Yi, Gunsu Yun, 2024, POSTECH, KFE)

KAIST UNIST POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Integration On-Going – PCS Simulator

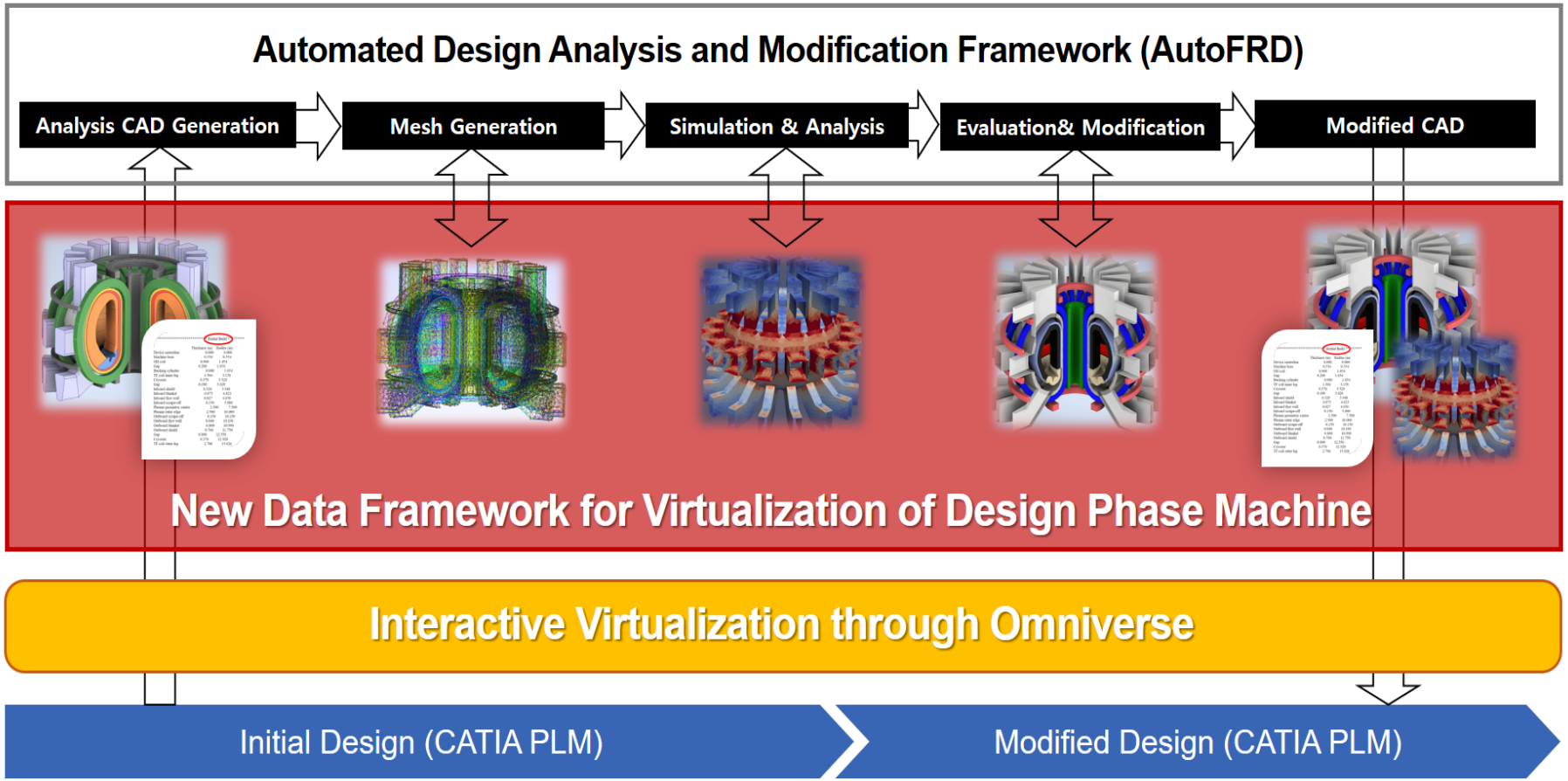
- A coordinated development both for KSTAR PCS upgrade and V-KSTAR control simulation capability
- Implementation of PCS simulator combining
  - Existing GA-TokSys simulator blocks are reviewed for preview simulation purposes
  - Newly developed coil controller (aka KCURR) based on ITER PCSSP is benchmarked in the closed-loop simulations in the KSTAR sides



Schematic of PCS Simulator for V-KSTAR (Sang-hee Hahn, KFE, 2025)

New Data Framework for Design Phase Machine

- Aim data configuration management following CAD design flow based on open SW technologies – Git & DVC
- On-going works to connect new data framework to the reactor design platform AutoFRD



Jae-Min Kwon et al, "Development of a data framework for conceptual design of fusion reactor", Wed Poster

Future Direction of WILL

- For operating machine → advanced monitoring and experimental analysis tool in virtual environment
- For design phase machine → tool enabling coordinated physics simulation and engineering analysis
- 3D data platform to integrate and enrich various fusion data