Virtual Tokamak for Integrated Physics and Engineering Analysis

Jae-Min Kwon[1+], Chanyoung Lee[1], T. Rhee[1], Jinseop Park[1], Minho Woo[1], Jaewook Kim[1], Juhyung Kim[1], Kimin Kim[1], Sang-Hee Hahn[1], Taeuk Moon[2], Eisung Yoon[2], Jaesug Ki[3], Chogang Lee[3], Jungeun Lee[3], Gyochan Hwang[3] G, Jae-seok Lee[1,4], Y.-c. Ghim[4]

[1]KFE, Korea; [2]UNIST, Korea; [3]Tri-Tech, Korea; [4]KAIST, Korea;
+Corresponding Author: *jmkwon74@kfe.re.kr*

Recent progresses in the development of a virtual tokamak platform are reported, which aims to integrate physics simulations and engineering analyses for fusion R&D. The virtual tokamak platform **WILL** (**V**ersatile **V**irtual platform for **I**ntegrated fusion simu**L**ation and ana**L**ysis) enables these integrations by bridging various data from tokamak machine operation, experiment, and simulation in flexible and seamless ways.

The **WILL** inherits most of enabling technologies and software developed for the Virtual KSTAR [1, 2], and modularize and restructure them by separating KSTAR specific features and generalize them for arbitrary tokamak device. The key technologies and software are 1) unstructured meshes to discretize arbitrary complex 3D models and store physics and engineering data, 2) the dedicated data framework to handle various fusion data based upon the IMAS and HDF5 technology, 3) python and C++ libraries for 3D data analyses such as collision detection of dynamic and static objects, and 4) 3D visualization software based on the graphic engines Unreal and Unity3D.

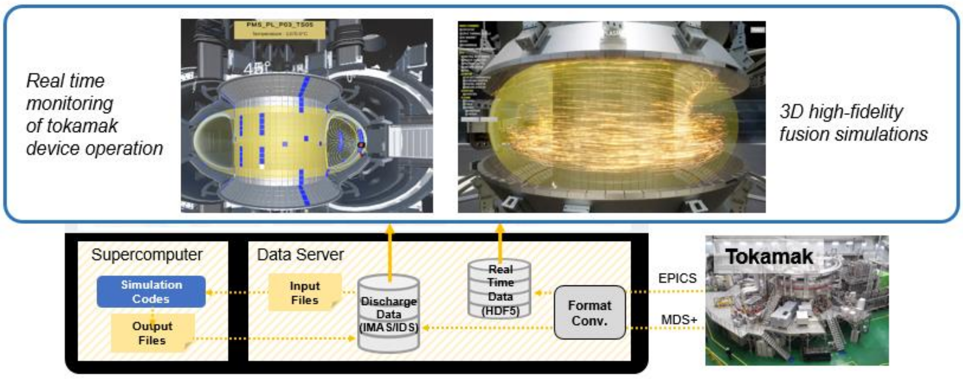

Figure 1. The overall schematic of virtual tokamak platform WILL.

Figure 1 shows the schematic of the **WILL**, which is connected to an operating tokamak device. Different types of data can be generated with various formats from operating device. For example, machine operation-related data are generated in real time with the EPICS format and plasma experiment-related data are produced in a shot-by-shot manner with MDS+ format (e.g. KSTAR case). The real time EPICS data can be converted into the HDF5 format and stored in the dedicated data server. Simultaneously, particular data set can be selected and funneled into the 3D visualization client, which then analyze and visualize them in real time. Currently, several types of real time data can be handled – real time EFIT reconstruction, temperatures of plasma facing components, and helium temperatures in superconducting magnets etc. The graphic engine Unity3D is utilized to implement the 3D visualization client for real time data processing.

Employing this real time capability of the **WILL**, various real time monitoring system can be implemented and customized according to specific use cases. Figure 2 shows the examples of real time monitoring systems for tokamak operation. Plasma equilibrium can be reconstructed and visualized as shown in the figure, where the plasma is represented as half-transparent yellow volume and the last closed flux surface is denoted as the red curves. The X-point and the divertor striking points can be identified and recorded using the collision detection algorithm and unstructured meshes employed in the platform. Another example is the real time monitoring system for superconducting central solenoid coils. As in the figure, both the status of total magnetic fields and the helium temperatures circulating the coils can be monitored. These information are crucial to determine the proximity of the status of the coils to the quench condition and systematically monitored and recorded using the monitoring system. It should be noted that the platform **WILL** enables systematic integration of real time streaming data, upon which various analyses can be performed along with 3D visualizations.

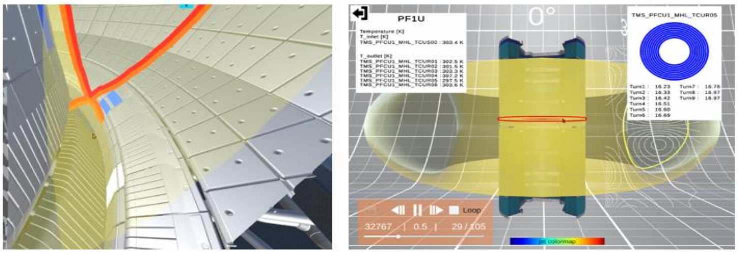

Figure 2. The real time monitoring systems enabled by WILL.

The **WILL** is connected to a dedicated computing resource, which is utilized for data analyses and simulations. Various fusion simulations and data analyses with engineering relevant model fidelities can be integrated into the platform. As for data analysis, one prime example is the Bayesian IDA (Integrated Data Analysis) for diagnostic data reconstruction. For example in KSTAR, the density profile reconstruction is performed combining data from the Thomson scattering system, two color interferometry, and beam emission spectroscopy for more reliable and robust reconstruction. The reconstructed profile data are then utilized for other data analyses and simulations.

Several simulations are being integrated into the **WILL**: 1) Monte Carlo NBI simulation of NBI fast ions, 2) ECH ray-tracing, 3) field-line tracing of 3D magnetic field perturbations by RMP, 4) synthetic diagnostics for Lyman-alpha neutral particle diagnostics, and 5) full 3D eddy current simulation. Details of these simulations will be presented in the conference though, we'd like to emphasize the importance of integrated data handling for simulation geometry (i.e. CAD models). These simulations share similar numerical methods related to model discretization and mesh. Also, they utilize the same data analysis techniques derived from the 3D data analysis libraries packaged in the platform.

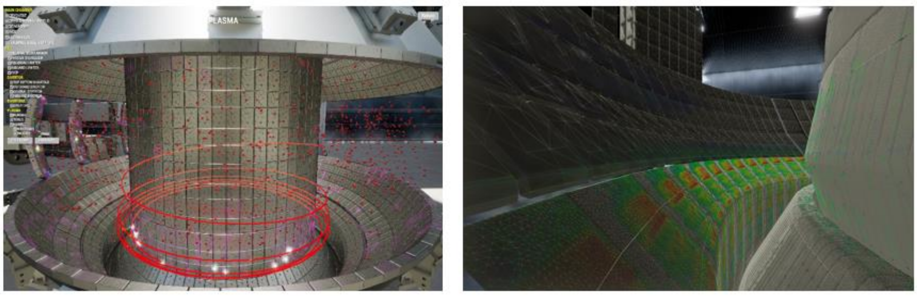

Figure 3. 3D high fidelity simulations enabled by WILL.

Figure 3 shows the examples of 3D simulations and their visualizations. In the figure, NBI particles are traced until they hit the plasma facing components. After detecting and locating the collisions of the lost particles and machine components, they are recorded and analyzed. Similarly, other elements such as EM waves, rays, and magnetic fields are traced, and their interactions with machine components can be recorded and analyzed. The right subfigure shows such an example, in which RMP-induced heat flux perturbations are analyzed and visualized.

The platform **WILL** has many potentials for the multiple-frontiers of fusion R&D. As an integrated 3D data platform, the **WILL** provides a natural tool to develop AI/ML models for fusion. Currently, the highest priority development goal is the plasma control simulation capability within the platform. Along with additional synthetic diagnostics, which can be readily added to the platform, the **WILL** is expected to `provide a platform for virtual fusion experiment aiming for reactor design and operation in future.

[1] Jae-Min Kwon et al, Fusion Eng. Des. 184, 113281(2022).
[2] Jae-Min Kwon et al, IEEE Trans. Plasma Sci. https://doi.org/10.1109/TPS.2024.3390159.