IMMERSIVE VR-BASED VISUALIZATION AND ANALYSIS OF FUSION PLASMAS USING DIGITAL-LHD AND VIRTUAL-LHD.

[1]H. OHTANI, [1]K. OGAWA, [2]N. OHNO and [3]A. KAGEYAMA

[1]National Institute for Fusion Science, Toki, Japan
[2]University of Hyogo, Kobe, Japan
[3]Kobe University, Kobe, Japan

Email: ohtani.hiroaki@nifs.ac.jp

At the National Institute for Fusion Science (NIFS), advanced visualization and analytical techniques using large-scale virtual reality (VR) systems and head-mounted displays (HMDs) are being developed for the interpretation of various fusion plasma datasets. In particular, the three-dimensional (3D) time-series trajectories of dust particles observed in the Large Helical Device (LHD) experiments have been projected into immersive VR space alongside magnetic field line data, enabling detailed investigations into dust transport phenomena. In the LHD deuterium plasma experiments, the trajectories of triton particles generated through fusion reactions and their collisions with plasma-facing components were computed. As a novel visualization approach, both the impact points and the velocity vectors at the collision moments were rendered in the VR environment. By combining orbit calculations with VR visualization of impact points and velocity vectors, we confirmed for the first time that triton collisions on the rear side of the divertor plates — a phenomenon not previously recognized with conventional methods — with VR providing an intuitive complement to conventional methods. VR is powerful for practical applications and understanding physics. Enhanced intuitive insight through VR can lead to new discoveries, better plasma control, and optimized reactor design.

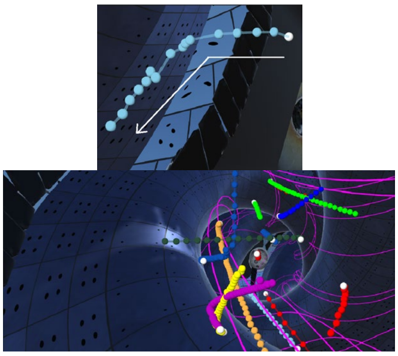

Fig.1 Top: VR visualization of the 3D time-series trajectory of a single dust particle by Digital-LHD using HMD. The particle's temporal path is rendered as a connected line, with the white sphere indicating the initial position and the white arrow denoting the direction of motion. Bottom: Visualization of multiple dust particle trajectories in 3D time-series format, shown together with a magnetic field line streamline in a stochastic region, viewed along the toroidal direction.

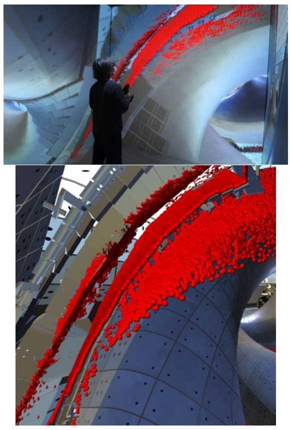

Fig.2 Top: VR visualization of the interior of the LHD vacuum vessel by Virtual-LHD using *CompleXcope*. Bottom: Triton impact points (red spheres) overlaid on a 3D model of the closed-type divertor structure and the first wall of vacuum vessel.

In future fusion reactors, where in-situ diagnostics will be extremely limited due to high radiation and restricted accessibility, virtual environments constructed from simulation data will play an essential role in design validation, physics analysis, and operational prediction. Among these, VR provides an immersive platform that allows researchers to spatially comprehend complex 3D structures and behaviors—such as particle trajectories, magnetic field topology, and component interactions– that are difficult to interpret from 2D projections or static 3D CAD models.

NIFS introduced the room-sized VR system CompleXcope in 1997, which enables users to immerse themselves in a full-scale scientific environment, recognizing its high potential for scientific applications beyond 3D CAD visualization [1]. Recently, the availability of affordable, compact, and easy-to-use head-mounted displays (HMDs) has enabled broader deployment of VR visualization in fusion research. At NIFS, HMD-based applications have been developed for both scientific analysis and education. While 3D CAD tools provide static models, VR allows interactive exploration of time-dependent phenomena, such as particle trajectories and evolving field structures, within the same spatial geometry.

One such application is Digital-LHD, a VR program that visualizes LHD plasma equilibrium data generated by the HINT code. It displays magnetic field lines, pressure isosurface, and drift particle trajectories in an immersive environment [2]. Digital-LHD also allows visualization of 3D time-series trajectories of dust particles observed in LHD plasma experiments as shown in Fig.1. While experimental observation is limited to views from external ports, the VR environment enables observation of dust trajectories from arbitrary directions. Moreover, by displaying magnetic field line streamlines simultaneously, it becomes possible to investigate the 3D spatial relationships between dust particle motion and magnetic topology. Digital-LHD also supports interactive on-demand calculation of drift particle orbits. By visualizing these trajectories together with magnetic field line data, users can explore the structural interplay between magnetic geometry and drift motions. The program has proven effective in enhancing graduate-level education in fusion science.

From 2017 to 2022, NIFS conducted deuterium plasma experiments in which ~1 MeV tritons were generated via beam–thermal D–D reactions. Material samples placed inside the vacuum vessel allowed for tritium retention analysis. To interpret the spatial distribution of triton impacts, we simulated their trajectories using a Lorentz orbit code and computed collisions with polygonal models of plasma-facing components generated from STereoLithography (STL) files. Figure 2 shows these impact points (red spheres) by VR software Virtual-LHD into the VR space, helping to determine optimal sample locations.

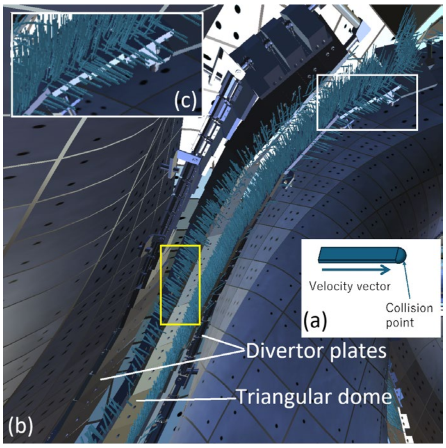

Fig.3: Triton particle collisions with the closed-type divertor and the triangular dome structure by Virtual-LHD.

Currently at NIFS, detailed analyses of tritium retention are being conducted by removing the divertor plates and first wall components and examining the tritium content within the plasma-facing materials. In support of this effort, the collision points of triton particles with the plasma-facing components were visualized in VR as spheres, and their velocities at the moment of impact were represented as triangular prisms originating from the impact points, indicating the direction of the velocity vectors [3] (Fig.3(a)). This representation enables intuitive, 3D observation of the incidence angles at which tritons collide with structural components, providing valuable insight into the interaction geometry between energetic particles and the inner wall surfaces of the device. Figure 3(b) demonstrates collision behavior at closed-type divertor plates. This indicates that while most triton particles collide with the front surface of the divertor plates (as seen in Fig. 3(b), where they travel from left to right, particularly within the yellow square), some tritons also reach and impact the rear side of the divertor plates (as shown in the white square, which is magnified in the upper-left (c) panel). This insight could only be clearly recognized through VR, where simultaneous visualization of velocity vectors at the impact moment provided an intuitive confirmation beyond orbit calculations. Furthermore, it was revealed that triton collisions are concentrated near the vertices of the triangular dome located at the center of the closed divertor structure. These localized impact distributions have also been confirmed through tritium retention analysis in the plasma facing wall plates.

The observation that tritons can travel complex trajectories and strike the rear surface or concealed first walls is of great importance for reactor design and operation. Digital-LHD and Virtual-LHD allow interactive on-demand calculation of particle trajectories and magnetic field lines from any point within the VR space. By tracing backward from the impact points, the origins and transport paths of particles can be identified, which provides essential information to design control strategies for reducing wall erosion and optimizing divertor performance. Furthermore, efforts are underway to incorporate information on the local particle flux density at the collision points, as this would enhance the interpretation of material analysis data.

Historically, collision distributions were projected onto 2D planes from 3D simulations for tritium retention studies. In contrast, immersive VR observation provides a more intuitive understanding of impact behavior and strengthens correlation with experiments. Importantly, these visualizations revealed that many tritons strike first wall components beyond the divertor region, knowledge that can guide control-oriented strategies to mitigate such undesirable impacts and contribute to improved reactor design.

To prevent such undesirable collisions, modifications to the magnetic field structure are required, necessitating changes to coil currents for plasma control or even to coil geometries for design. Yet, the design–simulation–visualization workflow, including magnetic field computation, triton orbit tracing, collision analysis, and VR rendering, is highly labor-intensive. To address this challenge, we are currently developing surrogate models that predict the loss particle distribution patterns for several different magnetic configurations using machine learning techniques. Furthermore, we plan to incorporate VR-based visualization of plasma control sequences executed by the ASTI system in LHD operations [4]. Our aim is to achieve real-time visualization of simulated results, integrated with 3D CAD models, within the VR environment. Such real-time VR-based analysis will contribute to improved plasma control and facilitate the design optimization of future fusion reactors beyond LHD. Importantly, in future reactor-scale devices, where in-situ diagnostics will be limited due to harsh environments, virtual environments based on simulation data will be essential tools for design, monitoring, and interpretation. The use of HMDs, which offer accessible and high-fidelity visualization capabilities, is expected to play a vital role in enabling intuitive interpretation of complex simulation results in fusion science.

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