

CONFERENCE PRE-PRINT**IMMERSIVE VR-BASED VISUALIZATION AND ANALYSIS OF FUSION PLASMAS USING DIGITAL-LHD AND VIRTUAL-LHD**

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Abstract

At the National Institute for Fusion Science (NIFS), advanced visualization and analysis techniques using large-scale virtual reality (VR) systems and head-mounted displays (HMDs) are being developed to interpret various fusion plasma datasets. In particular, by projecting three-dimensional (3D) time-series trajectories of dust particles observed in the Large Helical Device (LHD) experiments into an immersive VR environment together with magnetic field line data, detailed analyses of dust transport phenomena have become possible. In deuterium plasma experiments in the LHD, trajectories of triton particles generated by fusion reactions and their collisions with plasma-facing components were computed. As a new visualization method, the collision points and the velocity vectors at the moments of impact were displayed in VR space. By combining orbit calculations with VR visualization, triton collision events occurring behind the divertor plates—which had not been recognized by conventional methods—were identified for the first time. VR serves as an intuitive complement to conventional approaches, providing a powerful tool for both physical understanding and practical applications. The enhanced intuitive comprehension enabled by VR is expected to lead to new discoveries, advanced plasma control, and optimized reactor design.

1. INTRODUCTION

In future fusion reactors, in situ diagnostics will be extremely limited due to high radiation environments and restricted access, making virtual environments constructed from simulation data indispensable for design validation, physical analysis, and operational prediction. Within this context, VR provides an immersive platform that enables researchers to intuitively grasp complex three-dimensional (3D) structures and behaviors—such as particle orbits, magnetic field configurations, and interactions with components—that are difficult to understand through two-dimensional projections or static 3D CAD models.

In 1993, the University of Illinois at Urbana-Champaign developed an immersive virtual reality (VR) system [1]. Recognizing the high potential of immersive VR systems for scientific research, NIFS introduced its own immersive VR facility in 1997, named CompleXcope. Since then, dedicated visualization software for VR and a variety of applied research projects have been actively pursued [2]. In recent years, the widespread availability of low-cost head-mounted displays (HMDs) with high resolution, wide field of view, compact size, and user-friendly interfaces has further accelerated this trend. At the same time, the development environment for VR visualization software has become more accessible, with game development engines and related platforms facilitating the creation of sophisticated applications. As a result, VR visualization has been expanding not only in fusion research but also across diverse scientific disciplines. At NIFS, applications using HMDs have been developed for both scientific analysis and education. In contrast to 3D CAD tools, which provide static models, VR offers the advantage of interactively exploring dynamic phenomena such as the time evolution of particle orbits and magnetic field structures within the same spatial geometry.

VR visualization of fusion plasma data is gaining attention in recent years. For example, N. Bhatia et al. proposed a workflow to handle and visualize complex and large-scale experimental and simulation data [3]. G. Foss et al. demonstrated immersive VR visualization of laser plasma simulation results [4]. S. Gazzotti et al. applied VR/AR visualization techniques for fusion reactor design [5]. Most of these efforts focus on displaying CAD models of devices overlaid with simulation results, primarily for observational purposes. On the other hand, our group has investigated VR visualization of Large Helical Device (LHD) plasma equilibrium with 3D CAD data of LHD vacuum vessel, divertor plates, and heating antennas, VR visualization of time-series data, integration of spatial audio and visualization, and so on [2]. Our VR-based visualization analysis system fully exploits the interactivity that is inherent to VR environments. This interactivity allows users to actively engage with the data rather than merely observing it. For instance, users can freely place starting points for magnetic field line visualization anywhere within the 3D VR space. Through such interactive functionality, the system enables active exploration and analysis of both simulation and experimental datasets, going beyond passive viewing and fostering deeper insight into the underlying physical phenomena.

In this paper, we propose a visualization framework that integrates virtual-reality (VR) systems with plasma simulation and experimental data analysis, and we discuss its applications to plasma-wall interaction studies in LHD. We present VR-based visualization and analysis software for the LHD equilibrium plasma, designed for use with a head-mounted display. The developed visualization system is utilized not only for research purposes but also as an educational tool in graduate-level instruction and in outreach activities introducing fusion plasma to high school students. Furthermore, a new visualization technique has been implemented in the VR platform CompleXcope to analyze how triton particles interact with and collide against the plasma-facing wall. Through these visualization functions, including magnetic field line tracing and triton orbit analysis, we discuss how the system contributes to plasma control studies and fusion reactor design.

The structure of this paper is as follows. Section 2 describes the VR systems and software development environments at NIFS. Section 3 introduces the VR application *Digital-LHD* developed for head-mounted displays (HMDs) and its functions for magnetic field and particle-orbit visualization. Section 4 presents the use of immersive visualization in *Virtual-LHD* for analyzing triton particle collisions with plasma-facing components in deuterium experiments. Finally, Section 5 discusses the significance of VR visualization for interpreting complex plasma behaviors and summarizes the conclusions of this study.

2. VIRTUAL-REALITY SYSTEMS AND SOFTWARE DEVELOPMENT ENVIRONMENTS AT NIFS

At NIFS, two types of VR systems are utilized: the immersive VR facility CompleXcope and the head-mounted display (HMD) Meta Quest 3.

CompleXcope [1] is constructed as a room with 3 m-long screens on the front, left, right, and floor surfaces. When an observer wearing liquid crystal shutter glasses enters this room, three-dimensional (3D) images projected on the screens are perceived in stereoscopic vision. Because the observer is surrounded by four projection screens, the entire field of view is covered with 3D stereoscopic images. The position and orientation of the shutter glasses are detected by a tracking system, and the stereoscopic images projected on the screens are dynamically updated according to the observer's viewpoint. This mechanism provides a deeper sense of immersion. Rendering is performed on a calibrated PC cluster consisting of two HP Z840 workstations. Each workstation is equipped with Intel Xeon processors, 128 GB of RAM, and two NVIDIA Quadro P6000 GPUs.

Although a variety of HMDs are available on the market, NIFS mainly employs the Meta Quest 3 [6] to advance VR visualization research. The Meta Quest 3 provides a wide field of view—110° horizontally and 96° vertically—allowing a broader portion of the virtual space to be perceived at once. Each eye is equipped with a high-resolution display of 2064×2208 pixels, delivering sharp images. The device includes 8 GB of DRAM and 512 GB of storage. For advanced visualization, Meta Quest 3 is connected to a PC via Oculus Link. The PC is equipped with an Intel Core i9 processor, 32 GB of RAM, and an NVIDIA GeForce RTX 4060 GPU, on which VR visualization software is executed.

Application development for CompleXcope is carried out using C or C++ with OpenGL and CAVELib [7]. CAVELib manages projection onto the four screens, synchronization with the shuttering of the liquid crystal glasses, and tracking functions. In contrast, VR visualization software for the Meta Quest 3 is developed using the Unity game engine [8], and, for portability across multiple types of HMDs, the OpenXR plugin [9] is also employed.

3. VR APPLICATION SOFTWARE FOR HMD: DIGITAL-LHD

The VR application developed for visualizing plasma fusion data using a head-mounted display (HMD) is called Digital-LHD [10]. This program visualizes LHD plasma equilibrium data generated by the HINT code. It is developed using Unity with the OpenXR plugin. In an immersive environment, Digital-LHD can display magnetic field lines, plasma pressure isosurfaces, and drift particle orbits (Fig.1). Furthermore, it can visualize three-dimensional (3D) time-series trajectories of dust particles observed in LHD plasma experiments. Unlike experimental observations, which are restricted to external viewing ports, this approach allows inspection from arbitrary directions [11]. The central panel of Fig.1 shows a view inside the LHD vacuum vessel from an outer observation port, corresponding to the field of view of the stereo high-speed cameras used to observe the dust particle trajectories, while the right panel displays a view from inside the vacuum vessel looking in the toroidal direction, obtained by moving the viewpoint of the VR observer. Using a VR system in this way allows observation of the target object from perspectives and directions that are impossible to access with actual experimental instruments.

In addition, by simultaneously displaying magnetic field streamlines, the spatial relationship between dust motion and magnetic field structures can be examined in 3D space. In Digital-LHD, the observer can freely select any point within the VR space as the starting position for on-demand streamline calculation of magnetic field lines. In the right panel of Fig.1, a single magnetic field line (shown in magenta) is displayed, starting from a point placed near the plasma core. The spatial relationship between the magnetic field streamline and the dust particle trajectories can be examined from any viewing direction. As a result of such observations, both dust particles moving along magnetic field lines and those crossing them have been identified. While specialists studying dust particles previously discovered this relationship on two-dimensional displays using dynamic parallax [12], in the VR environment even non-experts can easily recognize these spatial correlations.

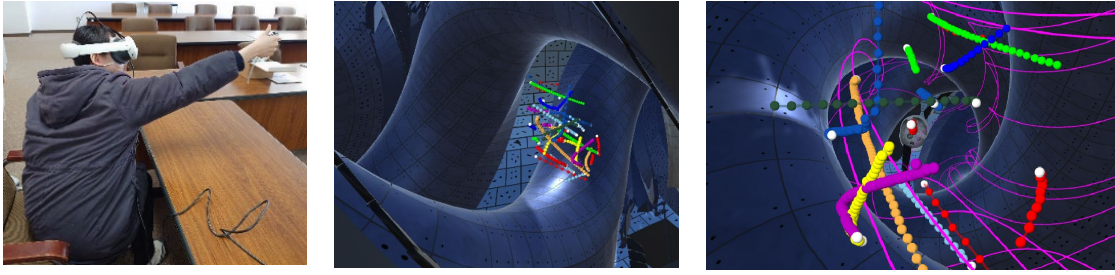


FIG.1. Operation using an HMD (left) and VR visualization of three-dimensional time-series trajectories of dust particles. The middle panel shows an observation from an outer port, corresponding to the actual viewing angle through the LHD outer port. The right panel shows the same data viewed from the toroidal direction together with magnetic field lines.

Digital-LHD also supports interactive on-demand calculations of drift particle orbits. By visualizing these orbits together with magnetic field streamlines, the relationships between magnetic configurations and both bouncing and passing orbits of drift particles can be observed, enabling detailed exploration of structural interactions between magnetic geometry and drift motion. Figure 2 shows VR visualization of a particle trajectory with a single magnetic field line. While the particle bounces near the peripheral region in the left panel, it passes in the core region in the middle panel. The particle orbit is calculated under the drift motion assumption. On the other hand, in the right panel, passing motion is displayed with gyration motion, which is calculated by the time-integration of Newton-Lorentz equation of motion directly. This program is also effective as an educational tool for enhancing graduate-level training in fusion science.

The VR visualization function for magnetic field lines and particle orbits is also implemented in Virtual-LHD, which will be described later.

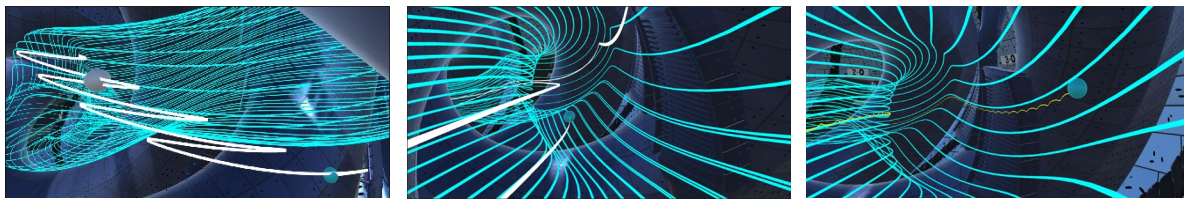


FIG.2. VR visualization of particle trajectory with magnetic field line. Left and middle panels show bouncing and passing particle trajectories, shown in white. The right panel displays passing particle trajectory shown in yellow, including the gyration motion. Sky-blue lines represent a single magnetic field streamline, the blue sphere represents a particle, and the white sphere indicates the starting point of the streamline. These objects are shown in the rendered LHD vessel.

4. TRITON PARTICLE COLLISIONS WITH PLASMA-FACING WALLS IN DEUTERIUM EXPERIMENTS BY VIRTUAL-LHD

Between 2017 and 2022, deuterium plasma experiments were conducted at NIFS in which ~ 1 MeV tritons were produced through beam-driven D–D reactions [13]. Tritium retention analyses were performed using samples installed inside the vacuum vessel. To interpret the spatial distribution of triton collisions, particle trajectories were simulated with a Lorentz orbit code, and collisions with plasma-facing components were calculated using polygon models generated from STL files [14]. For visualization of the collision points, the VR software Virtual-LHD [15] was employed to project the collision data into immersive VR space using CompeXcope. Virtual-LHD is a VR program for immersive visualization of LHD plasma equilibrium data generated by the HINT code, developed with C++, OpenGL, and CAVELib. It can display magnetic field lines, plasma pressure isosurfaces, and drift particle orbits in an immersive environment, while also projecting triton collision points as spheres superimposed on structural models of plasma-facing components within the vacuum vessel. This visualization enabled a clear understanding of the distribution of triton impacts on plasma-facing walls and provided guidance on optimal placement of material samples within the vessel [16,17].

At present, NIFS is conducting detailed analyses of tritium retention by removing divertor plates and first-wall tiles and measuring the tritium content in plasma-facing materials. To support these studies, a visualization function was developed in which triton collision points are displayed as spheres in VR, while the instantaneous velocity at the moment of impact is represented by triangular prisms emerging from the collision points, indicating the direction of the velocity vector (Fig.3, left). This representation allows the incident angles of tritons on structural surfaces to be intuitively observed in 3D, yielding valuable insights into the interaction patterns between energetic particles and device walls.

Figure 3 (right) illustrates the collision behavior on a closed divertor plate. While many tritons collide with the front surface of the divertor plate, it was also revealed that some reach and strike the rear side. This phenomenon was clearly identified only through VR visualization, providing an intuitive understanding beyond conventional orbit calculations. Moreover, it was found that triton collisions tend to concentrate near the apex of the triangular dome at the center of the closed divertor structure. Both the rear-side impacts on the divertor plate and the concentration of collisions near the dome apex were later confirmed by tritium retention analyses of plasma-facing wall materials. If you need to move a heading to the following page, please use a page break (usually found in word processing software under the ‘insert/page break’ menu. Please do not press return several times to move text onto a new page.

Figure 4 visualizes triton particle collisions near the open- and closed-structure divertor plates located close to the ceiling region of the LHD vacuum vessel. As shown in the left panel of Fig.4, triton particles collide with the first wall of the vacuum vessel and even reach the vessel wall behind the open-structure divertor. The right panel of Fig. 4 visualizes the distribution of triton particles colliding with the divertor plates. While the collisions on the cover surrounding the helical coils appear to occur at nearly uniform incident angles, collisions on the divertor plates occur with a wide range of incidence angles.

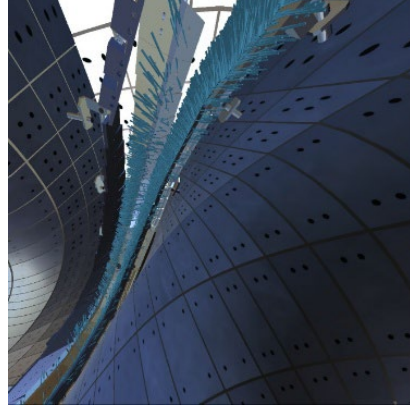
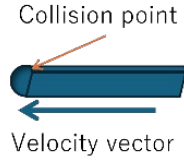


FIG. 3. Vector representation method and triton particle collisions with the closed divertor structure. The left panel illustrates the representation method for collision points and velocity vectors, where the vector direction is indicated from a sphere at the collision point rather than by arrows. The right panel visualizes triton particle collisions with the closed divertor structure and the central triangular dome.

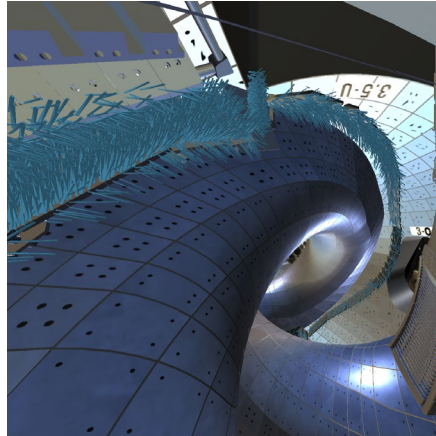
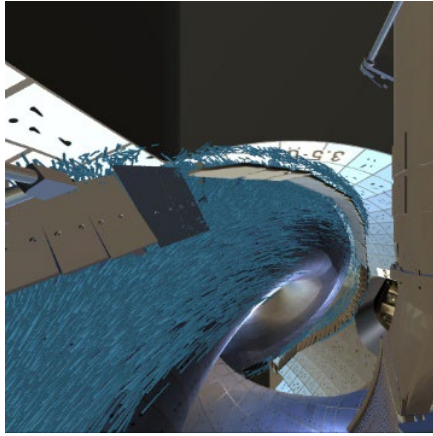


FIG. 4. Triton particle collisions with the first wall (left) and with open- and closed-structure divertor plates.

Tritons following complex trajectories and colliding with the rear side of divertor plates or with first-wall surfaces hidden behind them are of critical importance for reactor design and operation. In Digital-LHD and Virtual-LHD, particle orbits and magnetic field lines can be calculated on demand from arbitrary points within the VR space. By tracing backward from collision points, the origin and transport pathways of particles can be identified.

Figure 5 shows magnetic field lines displayed as streamlines. For example, when a starting point (indicated by a white sphere) is placed inside the vacuum vessel, Digital-LHD calculates the corresponding magnetic field line on demand and displays it as a streamline. By following this streamline, the origin of the magnetic field line can be determined. If the starting point is placed near the divertor plates, the transport path of particles carried along that magnetic field line can be identified. The same functionality is also available in Virtual-LHD.

This capability is essential for designing control strategies aimed at reducing wall erosion and optimizing divertor performance. Furthermore, efforts are underway to develop surrogate models based on machine learning to predict loss-particle distribution patterns across various magnetic configurations.

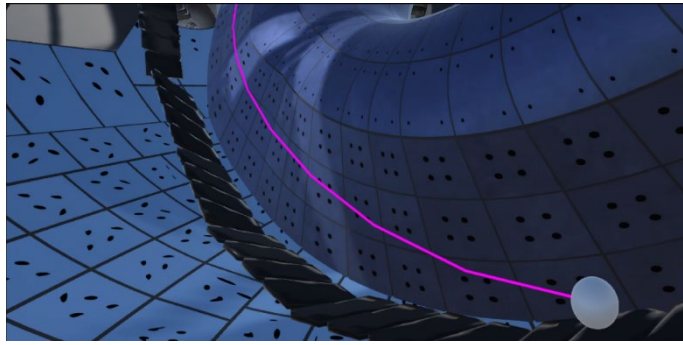


FIG. 5. Streamline visualization of magnetic field lines near the divertor.

5. DISCUSSION AND SUMMARY

Traditionally, studies of tritium retention have analyzed collision distributions by projecting three-dimensional (3D) simulation results onto two-dimensional (2D) planes. In contrast, immersive VR observation provides an intuitive understanding of collision behavior and strengthens correlations with experimental results. A key finding is that VR visualization revealed that many tritons collide not only in the divertor region but also with the first wall beyond it. This insight is valuable for the design of control-oriented strategies and contributes to improvements in reactor design.

Preventing such undesirable collisions requires modifications of the magnetic field structure, either by adjusting coil currents for plasma control or by altering the coil geometry itself. However, the design–simulation–visualization workflow—including magnetic field calculations, triton orbit tracking, collision analysis, and VR rendering—is highly labor-intensive. To address this challenge, efforts are now underway to develop surrogate models using machine learning that can predict loss-particle distribution patterns across multiple magnetic configurations. In addition, there are ongoing plans to visualize plasma control sequences from the LHD ASTI system [18] in VR, aiming for real-time VR visualization of simulation results integrated with 3D CAD models.

Such real-time VR analysis is expected to play a key role in improving plasma control and optimizing future reactor designs beyond LHD. In particular, for next-generation reactor-scale devices, where in situ diagnostics will be severely limited due to harsh environments, simulation-based virtual environments will become indispensable for design, monitoring, and interpretation. The increasing availability of high-resolution, user-friendly HMDs will further enhance intuitive understanding of complex plasma phenomena and accelerate the fusion research process.

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