INDICO：3523 Post Deadline Poster

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

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Outline

•**Recent progress in tritium retention analysis in LHD plasma-facing components**
→ VR-based visualization has proven effective for interpreting the results
→ Planning to submit as a post-deadline paper

•**Development of Digital-LHD: HMD-compatible VR visualization software for LHD plasmas**
→ Displays pressure isosurfaces, magnetic field lines, charged particle orbits, and dust trajectories
→ Utilized for data analysis and graduate-level education
•**Extension of Virtual-LHD: Large-scale CAVE-type VR visualization for LHD plasmas**
→ Visualizes triton collision points and velocities in VR
→ Clearly shows impact directions
→ Revealed collisions occurring on the rear side of divertor plates
•**VR is a powerful tool for both practical applications and understanding plasma physics**
→ Immersive VR visualization enhances intuitive understanding
→ Leads to new insights in fusion plasma research

•**One of key Features of VR-Based Visualization in This Study**
Utilizing one of VR's core strengths—**interactivity**—to its fullest extent, such as allowing the observer to place the starting point of magnetic field lines anywhere in the VR space.
→ Enables intuitive and flexible analysis of both simulation and experimental data.

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Recent Trends in VR-Based Visualization of Fusion Plasmas

- VR visualization of fusion plasma data is gaining attention in recent years.
  - N. Bhatia et al. proposed a workflow to handle and visualize complex and large-scale experimental and simulation data(Frontiers in Physics 13:1569248 (2025))
  - G. Foss et al. demonstrated immersive VR visualization of laser plasma simulation results(Photonics, 12(5), 436 (2025))
  - S. Gazzotti et al. applied VR/AR visualization techniques for fusion reactor design(Fusion Eng. Design, 172 (2021), 112780)
- Most of these efforts focus on **displaying CAD models of devices overlaid with simulation results**, primarily for observational purposes.

Key Features of Our VR-Based Visualization Analysis

- Fully utilizes **interactivity**, a core strength of VR.
- For example, **users can freely place starting points for magnetic field line visualization anywhere within the VR space**.
- Enables **active exploration and analysis** of both simulation and experimental data beyond passive viewing.

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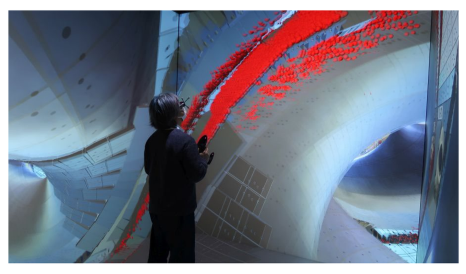
Hiroaki Ohtani et al: submitted to JoFE (2025).

VR Visualization Research at NIFS

- Utilizing both the large-scale VR system CompleXcope and advanced head-mounted displays (HMDs)
- VR-based visualization and analysis applied not only to fusion plasma data, but also to various types of scientific datasets
- Also actively used in graduate student education



VR visualization by the large-scale VR system CompleXcope

Operation with Head-Mounted Display (HMD)

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Development of Digital-LHD and Extension of Virtual-LHD

- VR visualization software that reads equilibrium plasma data from the **HINT code** for LHD
  → Displays **magnetic field lines, Poincaré cross-sections, isosurfaces of plasma pressure,** and **drift particle trajectories**
- **Interactive control** of:
  - Starting points for field lines and drift orbits
  - Isosurface threshold values
  - Poincaré section locations
  → All computed **in real time** within the VR environment
- **Digital-LHD[1]**: Newly developed for use with **head-mounted displays (HMDs)**
- **Virtual-LHD[2]**: for the **CompleXcope** VR system
  → Extended to include visualization of **triton impact points and velocity vectors at collision**

[1]Ohno, N. et al., PFR 19, 1401029 (2024).
[2]Kageyama, A. et al., Proc. 16th ICNSP, pp. 138–142 (1998).

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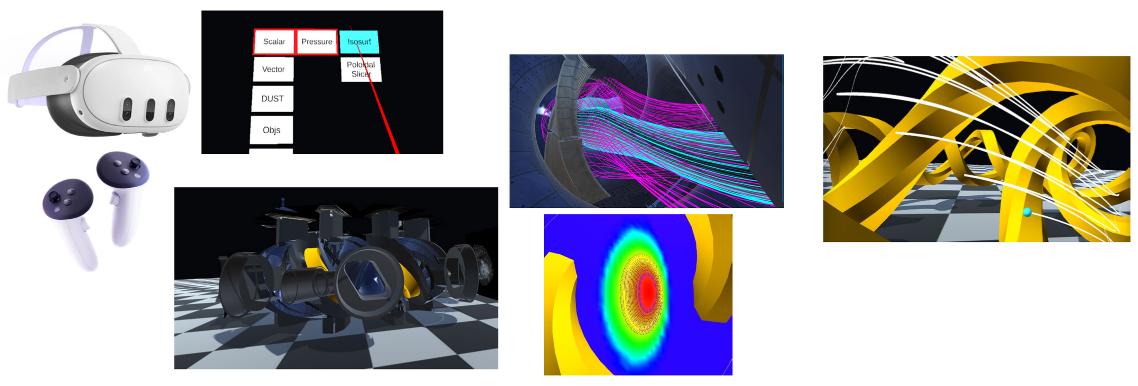
Digital-LHD: for HMDs

- N. Ohno et al.: PFR, Vol.19, 1401029 (2024)

- Isosurface and color map on poloidal cross section of plasma pressure
- Arrows and streamlines for vector field.
- Drift particle orbit with 3D sound
- Experiment observation data of dust particles



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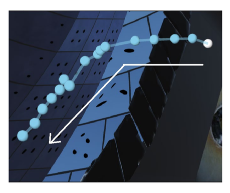
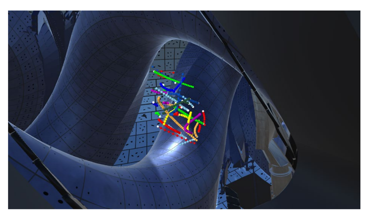
VR visualization of dust particles (Digital-LHD with HMD)

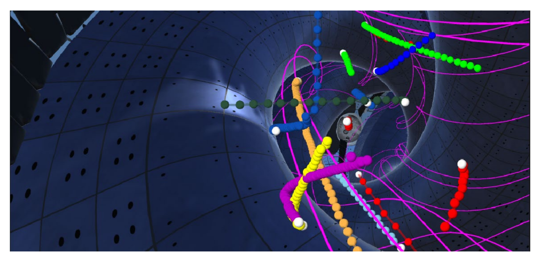
N.Ohno et al: PFR, Vol.19, 1401029 (2024)



3D time-series trajectory of single dust particle



View from outer port



3D trajectories of dust particles with magnetic field lines

- **Behavior of Dust Particles in the Edge Region**
- Dust particles are present **in the peripheral (edge) region** of the plasma
- **Most particles move along magnetic field lines,** but some exhibit **sharp curved trajectories,** crossing field lines and moving **radially inward**
- The **direction of particle transport varies depending on location**

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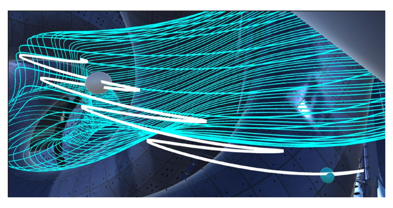
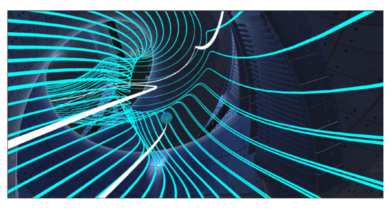
VR visualization of dust particles (Digital-LHD with HMD)

N.Ohno et al: PFR, Vol.19, 1401029 (2024)

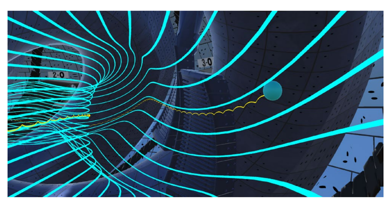
- Interactive on-demand calculations of drift particle orbits.
  - It is possible to put a starting point anywhere in VR world.
  - Together with magnetic field streamlines
  - The relationships between them can be observed.



Bouncing motion of drift particle



Passing motion of drift particle



Passing motion of particle, including the gyration motion

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M.Isobe, et al.: J. Plasma Fusion Res. SERIES, 8, 330.
R.Seki, et al.: Plasma Fusion Res., 14, (2019), 3402126.
K.Ogawa, et al.: Plasma Science and Technology, 21 (2019) 025102 (5pp)

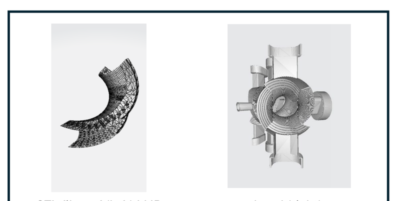
VR visualization of triton collision point on plasma surfacing wall

Trajectory calculation：LORBIT

- $m\frac{dv}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$
- Assumptions
  - No collision effect
  - Magnetic field in vacuum.
  - Disregard of electric field.
    - Because of energetic particles, it is assumed the effect of electric field can be ignored.
- Initial condition
  - Position：Generation distribution of triton determined based on the neutron generation distribution calculated by FIT3D-DD
  - Velocity: Isotropic distribution along parallel and perpendicular to the magnetic field

Collision detection

- The divertor plates are represented by the triangles based on the design data which was used in the installation of the divertors to the real LHD.
- Vacuum vessel and protective plate are displayed by the triangles based on the STL CAD data.
- Calculate whether the triton trajectory exists inside or outside the polygons
  →Detect whether the triton collides with the wall or not
- Intersection point of triton trajectory and the plasma facing
  → The special coordinate of the intersection and the velocity at the moment of collision are stored.



STL files of (left) LHD vacuum vessel and (right) protective plate.

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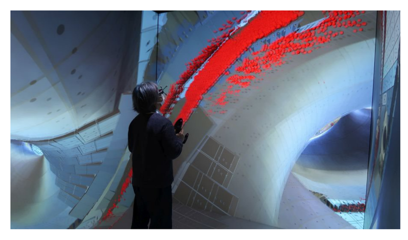
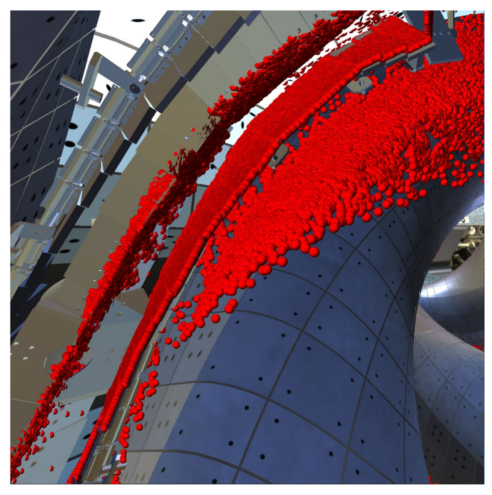
VR visualization of triton collision points (Virtual-LHD with CompleXcope)



CompleXcope



Sample placement locations for tritium analysis in the LHD deuterium experiments were determined using this VR visualization.

Kunihiro Ogawa et al: J. Instrumentation Vol.18 P01022 (2023)

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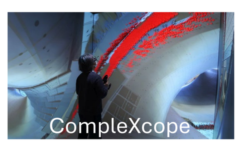
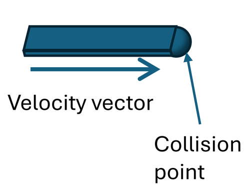
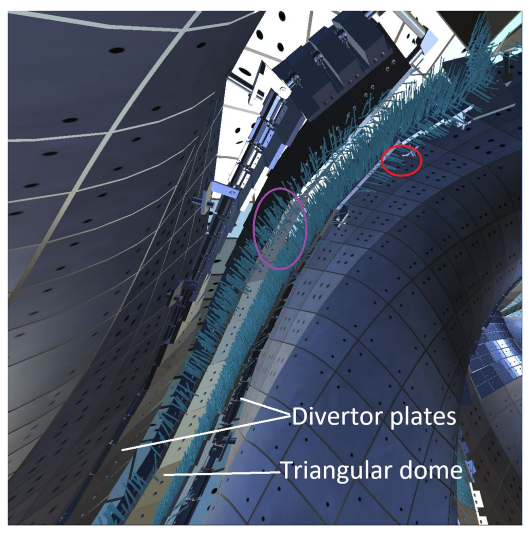
VR visualization of triton collision point and velocity vector (extended Virtual-LHD)







While most triton particles collide with the front surface of the divertor plates (they travel from left to right, particularly within the purple circles), some tritons also reach and impact the rear side of the divertor plates (as shown in the red circles). Triton collisions are concentrated near the vertices of the triangular dome located at the center of the closed divertor structure.

- **Collision points are visualized as spheres**, and **velocity vectors at impact are shown as triangular prisms.**
- **These localized impact distributions have also been confirmed through tritium retention analysis in the plasma facing wall plates.**

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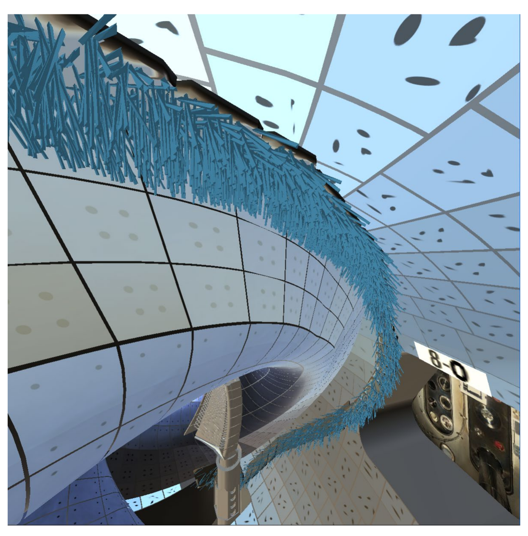
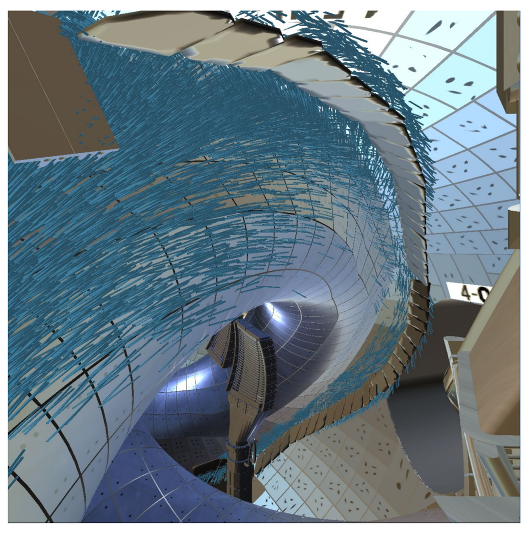
- Collision points on diveror plates
- Collision points on vacuum vessel wall





- The divertor plates are impacted at various angles.
- Impacts also occur on the vacuum vessel walls, such as the back side of the divertor plates

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Future plans

- **Advanced Capabilities of Virtual-LHD and Digital-LHD**
  - Real-time calculation of **magnetic field line streamlines** and **drift particle trajectories** from **any point within the VR space**
    → Developed for **backward-tracking of triton particle orbits**
    → Enables identification of the **origin of particles** that damaged plasma-facing components
- **Toward Design and Operation Improvements**
  - Some particles were found to collide with **first wall regions outside the divertor plates and the rear side of the divertor plates**
  - Using **machine learning**, the relationship between **magnetic structure and collision locations** is being modeled
    → Enables prediction of **impact location changes under different plasma conditions**
    → Supports **plasma experiments and future reactor design**
- **Real-Time Visualization of ASTI-Controlled LHD Experiments**
  - Real-time VR visualization of simulation results from **ASTI-based plasma control** in LHD
    → Integration of VR with real-time control and diagnostics framework

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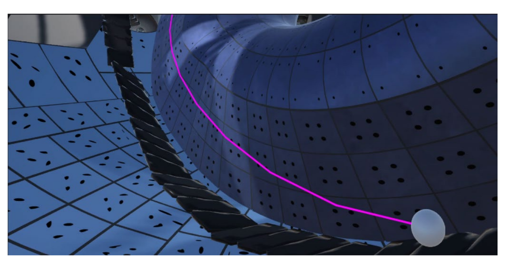
Streamline calculation

- Real-time calculation of **magnetic field line streamlines** and **drift particle trajectories** from **any point within the VR space.**
- You can put a starting point in the VR space, such as near the divertor plate, Virtual-LHD and Digital-LHD calculate the steam line of magnetic field.
- Virtual-LHD and Digital-LHD can also calculate of particle orbit from any point in the VR space.
- You can investigate their origin in the VR space.



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Summary

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→ Visualizes triton collision points and velocities in VR
→ Clearly shows impact directions
→ Revealed collisions occurring on the rear side of divertor plates

•**Digital-LHD & Virtual-LHD enable real-time calculation of magnetic field lines and particle trajectories**
→ Allows backward-in-time tracking of triton orbits
→ Makes it possible to trace the origin of colliding particles
•**VR is a powerful tool for both practical applications and understanding plasma physics**
→ Immersive VR visualization enhances intuitive understanding
→ Leads to new insights in fusion plasma research

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Acknowledgments
The author HO thanks Prof. Osakabe and Prof. Tanaka of NIFS for fruitful discussion. This work was performed with the support and under the auspices of the NIFS Collaboration Research program (NIFS24KIII001, NIFS25KIGM005), and it was partially supported by Grant-in-Aid for Scientific Research (C) (23K11128). This work was also performed on "Plasma Simulator" system of NIFS with the support and under the auspices of the NIFS Collaboration Research program (NIFS24KISI001).