Virtual-Reality Visualization of loss points of 1 MeV tritons in the Large Helical Device, LHD

Hiroaki Ohtani, Suguru Masuzaki, Kunihiro Ogawa and Seiji Ishiguro
National Institute for Fusion Science, Toki, Japan
The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan

Abstract

Intersection points of 1MeV tritons and the plasma facing wall are visualized in the vacuum vessel of Large Helical Device (LHD) with the divertor plates by the virtual-reality (VR) system. The trajectory of the energetic triton is evaluated by means of the collisionless Lorentz orbit code, and the strike point is calculated by the winding number algorithm. The intersection points of the tritons and the plasma facing wall are visualized as spheres with the rendered internal vacuum wall and divertor plates in the VR space, and it is possible to directly observe the strike points distributed on the wall and on the plates. It is found that many tritons intersect with the divertor plates and that some strike on the vacuum vessel. To evaluate the effectiveness of this VR visualization, we ask people to score the effect of experience and the level of understanding after finding the place where many particles attack on the plasma facing wall on the two-dimensional plane or in the VR space. This visualization helps us to determine where the material probes should be placed on the plasma facing wall in the real LHD for experimental analysis of the accumulated tritium on the plasma facing wall. This development of VR visualization will make a significant contribution to the fusion plasma research.

1. Introduction

To realize a fusion power generation system, we have many issues. Two of them are an efficient confinement of alpha particle generated by DT fusion reaction in a burning plasma, and tritium recycle in the fuel system.

In existing torus fusion devices, the energetic ion confinement has been studied instead of alpha particles [1]. For simulation study of alpha particle confinement, 1 MeV triton confinement is investigated in deuterium operations, since the Larmor radius and the precession frequency are the same as those of 3.5 MeV alpha particles generated by DT reaction [1, 2]. The deuterium experiments and the numerical simulation study have been performed in tokamaks for study of 1 MeV triton confinement [3, 4, 5, 6, 7]. In stellarator and heliotron, the orbit calculation was performed for the study of alpha particle or triton confinement property [8, 9]. The triton-burnup experiment in stellarator and heliotron was firstly performed in the first campaign of deuterium operations in March 2017 on the Large Helical Device (LHD) of National Institute for Fusion Science (NIFS), Japan [10, 11, 12, 13, 14]. In neutral-beam heated deuterium plasmas, neutrons and 1MeV tritons were generated by beam-thermal DD reactions. The orbit of 1MeV triton was calculated by means of the Lorentz orbit code to investigate dependence of the triton burnup ratio on the magnetic configuration [14].

On the other hand, tritium circulates in the fuel system of the fusion reactor. Tritium is burned up in the high-temperature plasma, and the plasma exhaust is removed from the vacuum chamber. The exhaust is processed through an isotope separation system that extracts the fusion fuels for reinjection into the vacuum chamber [15]. However, there are cases in which tritium stays in the unnecessary space and does not circulate. The amount of accumulated tritium is called tritium inventory. Increase of the tritium inventory causes the stagnation in the circulation of tritium and causes difficulty in the tritium operation. Since the tritium approaches directly to the plasma facing wall, there is concern over the increase of the inventory at the wall [16, 17, 18].

Since the first deuterium operations in LHD, the accumulated tritium on the plasma facing wall has been experimentally studied. After the experiments, we brought out the divertor plates which were used during the experiments and the material probes which were placed on the plasma facing wall, and analyzed the residual tritium in them [18,19]. Moreover, we also analyzed the accumulation of the energetic triton which collided with the divertor plates [20]. To analyze experimentally the energetic triton accumulation on the vacuum wall, we planned to put new material probes on the vacuum vessel of LHD. The probe is a rectangle holder with dimensions that are 42 mm by 15 mm by 7 mm, and five plate-like materials are inserted in the holder. It is necessary to place the probe on the appropriate position.

Visualization by means of a virtual-reality (VR) system is useful for deciding specifically the position of the material probe. Since National Institute for Fusion Science installed a CAVE-type VR system [21] named "CompleXope" in 1997, we have investigated VR visualization of plasma equilibrium data of LHD [22], and developed visualization software of CAVE-type VR system for numerical data [23]. In the visualization of experimental devices, there is a VR visualization system based on picture [24], an interactive VR operation system in which three-dimensional modeling data of fusion reactor components can be grasped by a virtual hand in the VR space [25], and investigation of assembly and maintenance processes by CAD software and VR system in the ITER project [26, 27, 28, 29]. Integral VR visualization of simulation, experiment and device data can help us to analyze the data since the integral VR visualization displays the simulation and the experiment data superimposed directly over device CAD data [30].

In this paper, the trajectories of 1MeV triton in the deuterium operations on LHD are evaluated by a collisionless full orbit calculation code, and loss points of the triton on the plasma facing wall are calculated as collision points on the divertor plates or the vessel wall.

The loss points are visualized in the three-dimensional VR space by CompleXcope integrally together with the components in the LHD, such as the divertor plates and the vessel wall. By this integral VR visualization, it is possible to grasp easily in what kind of distribution the collision points of tritons exist on the components in the LHD briefly, and to decide concretely where the material probes should be placed in the LHD.

In the remainder of the paper, we briefly mention the calculation method of the triton trajectory and the collision point with the plasma facing wall in Section 2, and we describe the VR visualization method of the triton collision points and the VR system we use in Section 3. The visualization results are shown in Section 4. The survey results of the efficiency of experience and the level of understanding are discussed in Section 5. Finally, we outline the conclusions of this paper and the feedback from the experiment experts.

2. Calculation of trajectory and loss point of triton

In the determination of the loss points of tritons on the plasma facing wall [14], we calculate the initial position of the triton from the triton generation distribution and evaluate the trajectory of the triton from the initial position. We calculate an intersection point of the triton trajectory and the wall as the loss point.

A triton generation distribution is given from a neutron generation distribution in the deuterium operations on LHD calculated by FIT3D-DD code [31]. To reproduce the triton generation distribution, we decided the initial positions of tritons, namely, radial positions, poloidal angle and toroidal angle by using uniform random numbers. The initial velocities are also determined by uniform random numbers under the condition in which the velocity distributions are isotropic along the parallel and perpendicular to the magnetic field, respectively.

We use the LORBIT code for calculation of triton trajectory [32]. In this calculation, the Newtonian equation of motion is solved without any collision effects. In this paper, we use the magnetic field in a vacuum which is calculated from the coil current of LHD. The effect of plasma is not included. In addition, we assume no electric field, because 1MeV tritons have the high energy and the effect of the electric field will be negligibly small on 1MeV triton orbits.

In this paper, tracking time of 1MeV triton orbit corresponds to 1ms. Since it takes more than 2sec for 1MeV triton to decrease its energy to 100keV [33], the tracking time is much smaller than the deceleration time.

We detect the intersection point of the triton and the plasma facing wall in the following procedure. The position and direction of the divertor plate are determined based on the design data which was used for the installation of the divertor plates in LHD. The surface of the divertor plate is constituted with triangles. Since the coordinate points of the vessel wall are determined by a row of points on each poloidal angle, the vessel wall is constituted with polygons which are formed by the row of points. We calculate whether the triton orbit exists inside or outside the triangles of the divertor plates or the polygons of the vessel wall by means of the winding number algorithm [34], and we detect the intersection point of the triton and the plasma facing wall. The intersection point is a loss point of triton. The coordinate point of the intersection point is stored in the Cartesian coordinate system, and the loss point position is three-dimensionally visualized in the VR space in the way described in the next section.

3. Visualization method of loss points of tritons

To visualize the loss point positions of tritons, we newly develop a VR visualization software for a CAVE-type VR system for this VR visualization based on the Virtual LHD [22] which was developed for visualization of the equilibrium LHD plasma. Since we do not have enough time before the experiment starts, we utilize the existing CAVE system and modify our developed software previously. The software includes an interface for reading the three-dimensional coordinate data of particles and a rendering function of particles by the point-sprite method [35] for visualizing the loss points as spheres. This software is written in C++ with OpenGL and CAVELib library.

The internal wall and divertor plates of the LHD are rendered by Unity [36] based on the CAD data which was used for construction of the real LHD. The version of Unity is 5.3.4 because we need to use the following software, FusionSDK [37].

To superimpose and display the spheres of triton loss points and the internal components of LHD, we use a commercial software, FusionSDK, which captures the OpenGL image data rendered by different visualization software, superimposes them in one VR space and displays them in real time [37, 38, 39].

The number of the triton loss points is 583,695 throughout the inside of the LHD. The number is too numerous to display in the VR space because the frame rate is reduced due to computer performance shortage. To avoid the reduction of the frame rate, we divide the data into ten data because LHD has ten times the rotation symmetry, and we extract three sections from ten data. Because the number of three-section data is still large, we display 30,000 points in this paper.

CompleXcope is a typical system which has four screens, that is, three on the walls and one on the floor, the size of which is approximately 3m x 3m. ARTTrack5 system tracks the position and viewing direction of the viewer's head by optical red-ray cameras [40]. The viewer uses a three-dimensional mouse called Flystick2, which is also monitored by the

ARTrack5 system. By means of the tracking system, the objects on the screens are redrawn according to the movement of the viewer and the instruction by the Flystick2. The projectors are MirageWU7K-M made by Christie. The liquid-crystal glasses are XPAND X105RF and the emitter system is Emitter Pro AE125RF made by XPAND. The computer resources of CompleXcope are as follows: two HP Z840 workstations with 64bit Windows 10. Each workstation has two Intel Xeon E5-2637v4 processors (Clock speed is 3.50GHz and the number of cores is four) and 128 GB memory. Two graphic cards NVIDIA Quadro P6000 are installed to each workstation. Four graphic cards are synchronized by Quadro Sync2.

4. Visualization results

Figure 1 shows that a viewer is watching the intersection points of tritons (red spheres) and the plasma facing wall in the vacuum of LHD in CompleXcope. In addition, the snapshots projected on the four screens of CompleXcope are indicated in Fig.2. Stereoscopic displayed objects are projected on the four screens of CompleXcope, and the stereoscopic images cover the entire visual field of the viewer who wears liquid-crystal glasses. By means of the tracking system of CAVE, the objects shown on the screens move according to the movement of the viewer in the CompleXcope and the viewer can also move the rendered objects in the VR space by pushing a joystick of Flystick2. As a result, the viewer is surrounded by stereoscopic images with a high immersion feeling and can look at objects that he/she is interested in with enlarging the images.

Figure 3 shows the three-dimensionally plotted intersection points with the divertor plates and the vacuum vessel which are projected on a two-dimensional figure, and the number of particles plotted on the two-dimensional plane as a function of toroidal and poloidal angles. These figures are made by the same plotting method as that used in Ref.[14] for discussion on the distribution of the points. Although these plots excel in the statistical analysis of the point distribution, they are not suitable for considering where the material probes should be placed in the LHD vessel. The visualization in this paper enables us to enter the virtual LHD vessel shown in the VR system with a high immersion feeling, and to analyze the intersection point distribution while looking directly at the intersection points of tritons and the plasma facing wall before our very eyes from various viewing points and directions. Moreover, by means of CAVE-type VR system, two or more persons can discuss the distribution while watching it together unlike head mount display, which is usually used by only one person. These features of VR visualization help us to determine the appropriate position of the material probe on the plasma facing wall for studying experimentally accumulated tritons on the wall in the real fusion reactor.

Here we show several snap shots recorded from the various viewpoints and lines of sight and discuss the intersection point distribution of the tritons and the plasma facing wall.

We observe closed structure divertor from the lower port of LHD in Fig. 4 and from another viewing point in Fig. 5. It is found that almost all the tritons collide with the closed divertor plates and that some tritons intersect with the triangle dome structure in the closed divertor system and the vacuum wall. The intersection points are distributed on the right divertor plates and the right side of the triangle domes. This bias of the intersection points results from an orbit deviation by the grad-B drift. When a direction of the toroidal magnetic field is changed conversely, the positions of the intersection points move to the left divertor plates and the left side of the triangle domes. This movement is confirmed by experiments and numerical simulations.

The intersection points on the open structure divertors observed from the front and from the side are shown in Fig. 6 and Fig. 7, respectively. In Fig.7, we can watch the points behind the divertors. While many particles collide with the open divertor plates, some particles also intersect with the vacuum vessel wall. It is found from Fig. 7 that some tritons intersect with the vacuum vessel wall behind the plate. As mentioned above, the energetic tritons which run away from the plasma confinement region with no collision intersect with the walls in the divertor region. It is found that many tritons collide with the divertor plates and that some tritons intersect with the vacuum wall. To confirm experimentally the intersection points of the energetic tritons and the plasma facing wall, we planned to place material probes on the wall. Since the divertor plates and vacuum wall displayed in the VR space are arranged at the same positions and directions as those in the real LHD vacuum, we can concretely and correctly examine where the probes should be set up on the plasma facing wall. As a result, we decided on three positions on the wall as shown in Fig. 8 and set three probes in the real LHD. The probe 1 was placed on the wall where many energetic tritons collide. The probe 2 was installed on the wall where the tritons intersect when the toroidal magnetic field was reversed, and the probe 3 was placed upon the wall where so many tritons did not strike with the wall.

We measured frame rates in this VR visualization by CompleXcope to examine the dependence of the frame rate on the number of particles which are displayed in the VR space with the component CAD data in the LHD. The results are summarized in Table 1. As the number of particles increases, the frame rates merely decrease. However, these frame rates are acceptable for displaying stereoscopic objects on the screen of CompleXcope with movement of the objects by the tracking system.

5. Effectiveness of this VR visualization

We check the validity of this VR visualization as follows; since the purpose of this VR visualization in this paper is that we find the place where the many tritons attack and determine the appropriate place to put the material probes on the plasma facing wall, we consider that to determine the place is a task. We ask multiple people to work this task watching the intersection points on the two-dimensional (2D) plane or in the VR space, and to evaluate the work efficiency and the understanding level. In the case of 2D plane, we show the figures shown in Figs. 2 and 9 on the 2D display, while in the case of VR space, we ask the people to enter the CompleXcope and experience the VR content we developed in this paper. Figure 9 drawn by the experiment researcher shows the CAD data of the closed divertors and the vacuum vessel wall with the strike points of the tritons on the 2D plane. The examinees are four LHD experiment researchers, five simulation researchers, two graduate students, two office workers of NIFS, nine high-school students and one high-school teacher. The office workers and six high-school students have no experience of the VR world before this survey. All examinees experience the task on the 2D plane and in the VR space to score the work efficiency and the understanding level from zero for bad to five for good. In the experience effect, they evaluate ease of finding the place where many particles attack, while in the level of understanding, they judge whether they convince the solution after we show the position where the experiment researcher determined.

Table 2 shows the average scores of each group. It is turned out that both work efficiency and the understanding level have a higher rating in the VR space compared with on the 2D plane for every group. The score of the work efficiency is a little lower in the cases of the simulation scientists and the high-school students. The reason is as follows; some of them evaluated that the task on the 2D plane was easy because the figures beforehand showed the place where many particles attacked, while the task in the VR space was not easy since they needed to walk-through in the vacuum vessel by the Flystick2 to find the place. When we asked them to draw the 2D figures by themselves, they said that the task became more difficult compared to the task in the VR space since they had to find the place by themselves. One simulation researcher said that the shadow in the 2D figure helped him to understand the three-dimensional structure and that the task on the 2D plane could earn a high grade.

One experiment scientist and one high-school student evaluated the understanding levels were comparable with each other on the 2D plane and in the VR space since they could confirm that the material probe was set on the appropriate place even on the 2D figures. The number of people who told us such an opinion was two, and the task in the VR space had a higher rating compared with that on the 2D plane.

One experiment scientist told us that her experience in the VR space has been profitable before she entered the real LHD and installed the material probes on the plasma facing wall. Since she could set up the probes while imagining the relationship between the position where the many tritons attacked in the VR space and the position where they installed the probes in the real LHD. In addition, after the LHD plasma experiments, she would be able to know which vacuum vessel tiles should be detached from the vacuum vessel wall in advance. This can improve the efficiency of analyzing the accumulation of the energetic tritons in the wall. In this way, the VR content we developed in this study serves the experiment well.

6. Conclusions

We calculated the trajectories of 1MeV tritons which were generated in the deuterium operations in LHD, and we found the intersection points of the tritons and the plasma facing wall. The strike points on the wall were visualized with the vacuum vessel wall and the divertor plates of LHD by the VR system 'CompleXcope'. It was possible to analyze the strike point distribution on the wall and the divertor plates. According to the analysis, the energetic tritons which ran away from the plasma confinement region without collision intersected with the wall in the divertor region. Many tritons had a collision with the divertor plates, while some tritons collided with the vacuum vessel wall.

One of the authors, S. Masuzaki, is an experiment researcher who planned to put the material probes on the plasma facing wall in the LHD and to analyze experimentally the energetic triton intersection points on the material probes. He used this VR system with his colleagues, that is, an experiment researcher and a software developer, together. While watching the VR visualization, the experiment researchers tried to find the appropriate positions of the material probes together, and he and the software developer discussed and confirmed the visualization results and their effectiveness at the same time. Through this VR visualization, they could determine the positions where many tritons attacked the wall and where the tritons did not intersect with the wall. They also took advantage of the CAVE-type VR feature, that is, the simultaneous experience of multiple people, at maximum this time. This VR visualization played an important role in the position determination of the material probes.

Because the CAVELib software developed in this paper for displaying the intersection points in the VR space can be ported to a head mount display (HMD) system easily, such as Oculus Rift, by using the wrapper program "CLCL"[41]. In this case, only the intersection points can be viewed on an HMD because the CAVELib software visualizes only the intersection points. FusionVR or FusionSDK is needed to superimpose and display the intersection points rendered by CAVELib software and the plasma facing wall CAD data rendered by Unity in one VR space integrally. It is unclear whether FusionVR or FusionSDK corresponds to the superimposition of the software with CLCL library and Unity. Our VR visualization software was developed using C++, OpenGL and CAVELib. If it can be ported using C# and Unity, it will be possible to display the intersection points and the wall CAD data integrally on an HMD.

In Section 5, the experiment specialist told us that she imagined the intersection points on the plasma facing wall displayed in the VR space while installing the probes in the real LHD. If she uses an augmented reality (AR) system or a mixed reality (MR) system, such as HoloLens 2, the intersection points rendered by computer graphics will be superimposed on the image of the real wall shown through the transmission lens. We plan to develop such system in future.

VR technology is a powerful tool for analyzing the data of simulation, experiment, device and so on. We believe the development in this paper will make rapid progress in fusion plasma research, and will accelerate collaboration among simulation, experiment, and reactor design research.

Acknowledgements

This work is performed with the support and under the auspices of the NIFS Collaboration Research program (NIFS19KNTS057, NIFS20KKGS026, NIFS20KOAH037), and by the LHD project budget (NIFS20ULHH003, NIFS20ULHH034). The author, OH, thanks to the people who cooperated on the survey written in Section 5.

Reference

[1] A. Fasoli, et al.: Physics of energetic ions. Nucl. Fusion, 47, (2007) S264

[2] W. W. Heidbrink and G. J. Sadler: The behaviour of fast ions in tokamak experiments. Nucl. Fusion, 34 (1994) 535.

[3] W. W. Heidbrink: Extending virtual reality simulation of ITER maintenance operations with dynamic effects. Nucl. Fusion, 23 (1983) 917.

[4] M. Hoek, et al: Triton burnup measurements at ASDEX Upgrade by neutron foil activation. IPP-Report (1999) IPP-1/320.

[5] H. H. Duong, et al.: Confinement of fusion produced MeV ions in the DIII-D tokamak. Nucl. Fusion 33 (1993) 211.

[6] T. Nishitani, et al.: Triton burn-up study in JT-60U. Plasma Phys. Control. Fusion 38 (1996) 355.

[7] J. Jo, et al.: Triton burnup measurements in KSTAR using a neutron activation systemRev. Sci. Instrum. 87 (2016) 11D828.

[8] S. Gori, et al.: α-particle confinement optimization in quasi-axisymmetric configurations. Plasma Phys. Control. Fusion 43 (2001) 137.

[9] S. Okamura, et al.: Low-aspect-ratio Quasi-axisymmetric Stellarator CHS-qa. J. Plasma Fusion Res. SERIES 3 (2000) 73.

[10] M. Osakabe et al: Current status of large helical device and its prospect for deuterium experiment. Fusion Sci. Technol. 72, 199 (2017).

[11] K. Ogawa et al.: Time-resolved triton burnup measurement using the scintillating fiber detector in the Large Helical Device. Nucl. Fusion 58 034002 (2018).

[12] M. Isobe et al.: Fusion neutron production with deuterium neutral beam injection and enhancement of energetic-particle physics study in the large helical device. Nucl. Fusion 58 082004 (2018)

[13] K. Ogawa et al.: Energetic ion confinement studies using comprehensive neutron diagnostics in the Large Helical Device. Nucl. Fusion 59 076017 (2019).

[14] K. Ogawa, et al.: Study of first orbit losses of 1 MeV tritons using the Lorentz orbit code in the LHD. Plasma Science and Technology, 21 025102 (2019).

[15] For example, https://www.iter.org/mach/FuelCycle

[16] R. Kasada et al: A system dynamics model for stock and flow of tritium in fusion power plant. Fusion Engineering and Design, 98-99, 1804 (2015)

[17] Z. Zhu, et al: A system dynamics model for tritium cycle of pulsed fusion reactor. Fusion Engineering and Design, 118, 5 (2017)

[18] S. Masuzaki et al: Investigation of remaining tritium in the LHD vacuum vessel after the first deuterium experimental campaign. Physica Scripta T170 (2020) 014068.

[19] M. Yajima et al.: Investigation on tritium retention and surface properties on the first wall in the large helical Device. Nuclear Materials Energy, 27 (2021) 100906.

[20] S. Masuzaki et al.: Investigation of the distribution of remaining tritium in divertor in LHD. Nuclear Materials and Energy, 26 (2021) 100884

[21] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti: Surround-screen projection-based virtual reality: the design and implementation of the CAVE. In: SIGGRAPH'93: Proceedings of the 20th annual conference on computer graphics and interactive. pp. 135–142

[22] A. Kageyama et al.: Data Visualization by a Virtual Reality System. Proc. 16th International Conference on the Numerical Simulation of Plasmas (ICNSP). 138

[23] A. Kageyama et al.: Immersive VR visualizations by VFIVE part 2: applications'. J. Model. Simulat. Sci. Comput., 4 (2013) 1340003.

[24] D. Li, B. J. Xiao, J. Y. Xia: High-resolution full frame photography of EAST to realize immersive panorama display. Fusion Engineering and Design, 155 (2020) 111545.

[25] N. Mizuguchi, et al: Development of reactor design aid tool using virtual reality technology. Fusion Engineering and Design, 81 (2006), 2755–2759.

[26] J. van Oosterhout et al.: Interactive virtual mock-ups for Remote Handling compatibility

assessment of heavy components. Fusion Eng. Design, 89 (2014), 2294-2298.
[27] C. J. M. Heemskerk et al.: Extending virtual reality simulation of ITER maintenance operations with dynamic effects. Fusion Eng. Design, 86 (2011), 2082-2086.
[28] J. van Oosterhout et al.: Haptic shared control improves hot cell remote handling despite controller inaccuracies. Fusion Eng. Design, 88 (2013), 2119-2122.
[29] N. Takeda et al.: Development of a virtual reality simulator for the ITER blanket remote handling system. Fusion Eng. Design, 83 (2008), 1837-1840.
[30] H. Ohtani, et al.: Integrated Visualization of Simulation Results and Experimental Devices in Virtual-Reality Space. Plasma Fusion Res. 6 (2011) 2406027.
[31] R.Seki, et al.: Evaluation of Neutron Emission Rate with FIT3D-DD Code in Large Helical Device. Plasma Fusion Res., 14, (2019), 3402126.
[32] M. Isobe, et al.: Lorentz alpha orbit calculation in search of position suitable for escaping alpha particle diagnostics in ITER, J. Plasma Fusion Res. SERIES, 8, 330.
[33] J. Wesson: "Tokamaks 3rd edn" (Oxford: Oxford University Press) (2004).
[34] K. Hormann, A. Agathos: The point in polygon problem for arbitrary polygons. Comp. Geometry, 20, (2001), 131.
[35] H. Ohtani, et al: Visualization of dust particle data with plasma simulation results using virtual-reality system. Contrib. Plasma Phys. Vol.56, No.6-8, (2016) 692-697.
[36] https://unity.com/
[37] https://www.fiatlux.co.jp/product/virtual/easyvr/
[38] H. Miyachi et al: Visualization pse for Multiphysics analysis by using opengl api fusion technique. IEEE Comp. Soc. (2005) 530.
[39] H. Miyachi et al: Network opengl fusion to make effective presentation system. IEEE Comp. Soc. (2007) 536.
[40] https://ar-tracking.com/en
[41] S. Kawahara and A. Kageyama: Development of CAVELib Compatible Library for HMD-type VR Devices. J. Adv. Sim. Sci. Vol.6 (2019) 234-248.

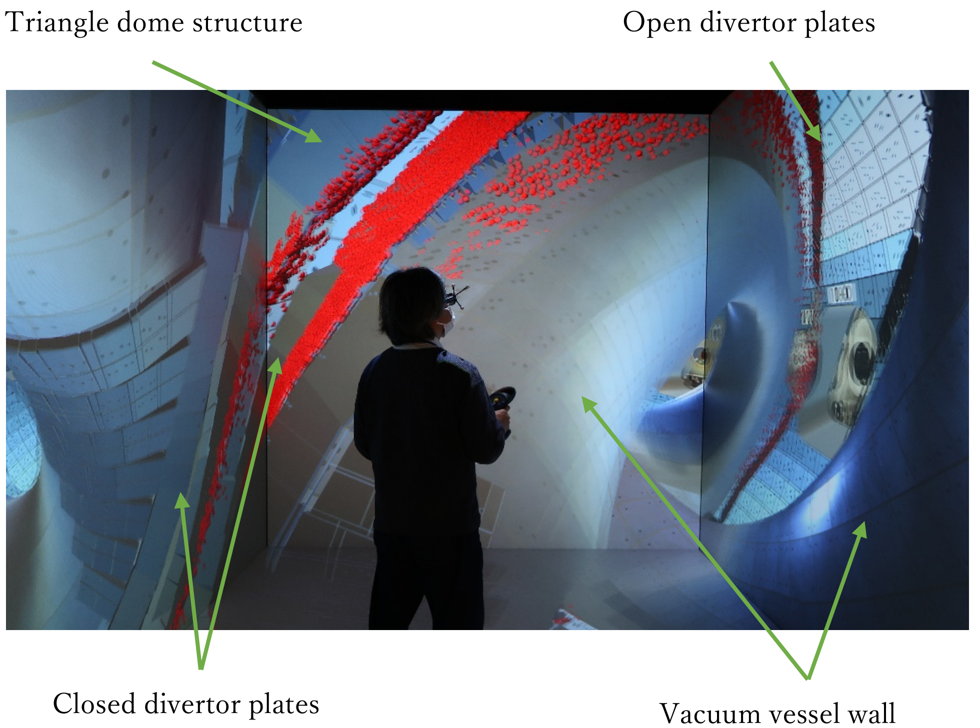
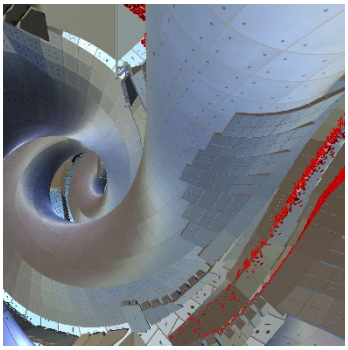
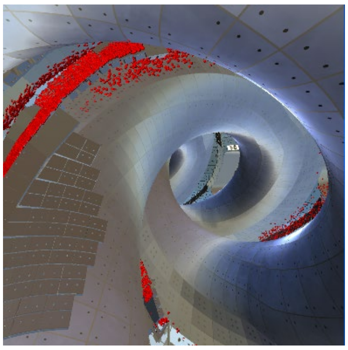


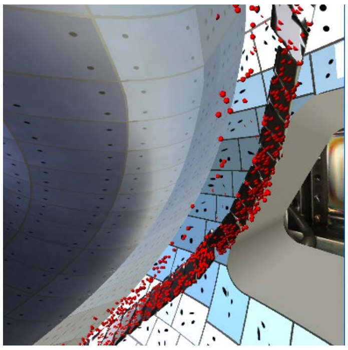
Figure 1. CompleXcope in which a viewer watches triton intersection points and the plasma facing wall. The plasma facing wall includes a vacuum vessel wall, open and closed divertor plates, and triangle dome structure. Red sphere indicates the intersection point of triton and plasma facing wall.



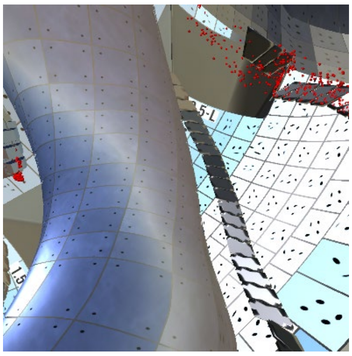
(a) Left screen.



(b) Front screen.



(c) Right screen.



(d) Floor screen.

Figure 2. Snapshots of plasma intersection points and plasma facing wall on the (a) left, (b) front, (c) right and (d) floor screens.

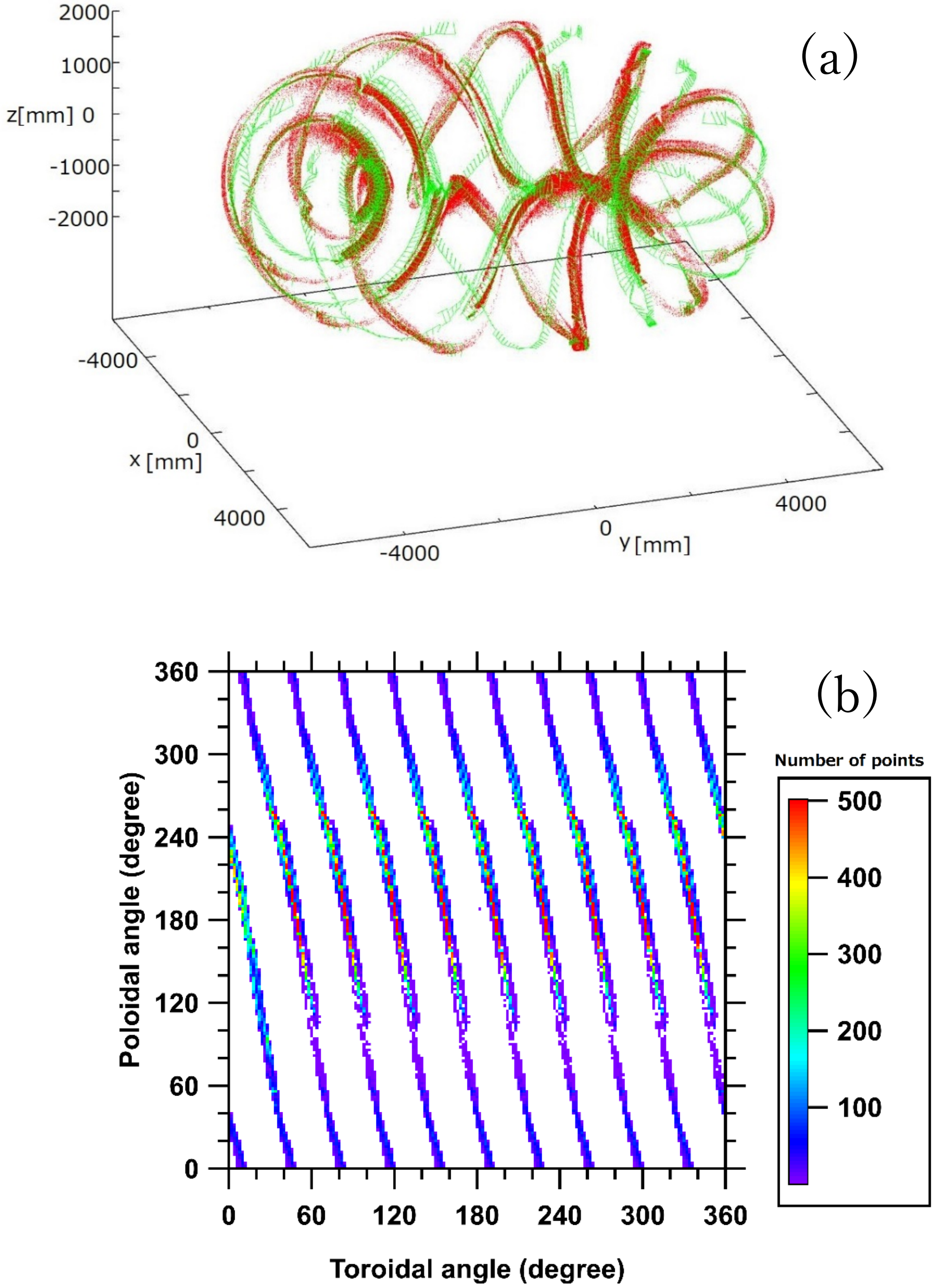


Figure 3. (a) The intersection points plotted in three-dimensional space with the divertor plates projected on two-dimensional space, and (b) the number of points on the two-dimensional plane as a function of toroidal and poloidal angles. In Fig.3 (a), the intersection points and the divertor plates are colored by red and green, respectively.

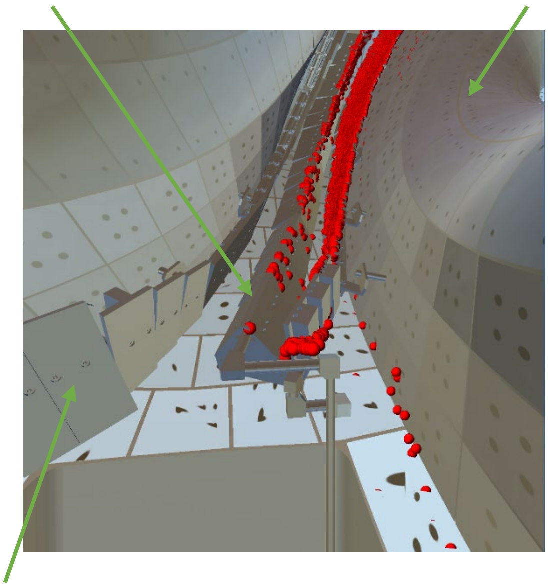


Figure 4. Closed divertor, triangle dome structure and vacuum vessel observed from the lower port.

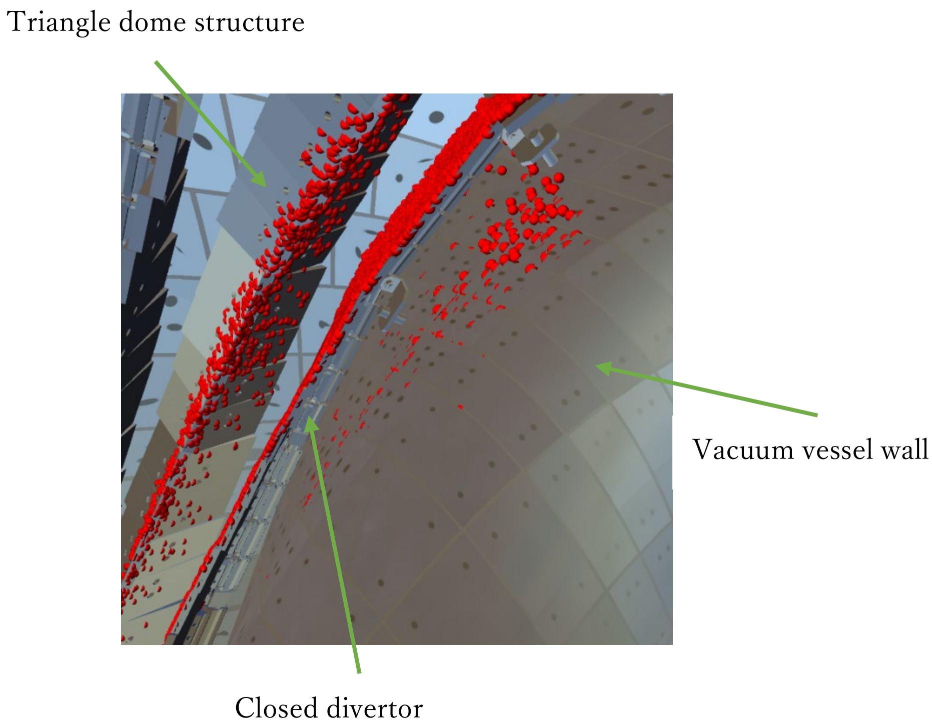


Figure 5. Closed divertor, triangle dome structure and vacuum vessel wall observed from another viewpoint other than Fig.4.

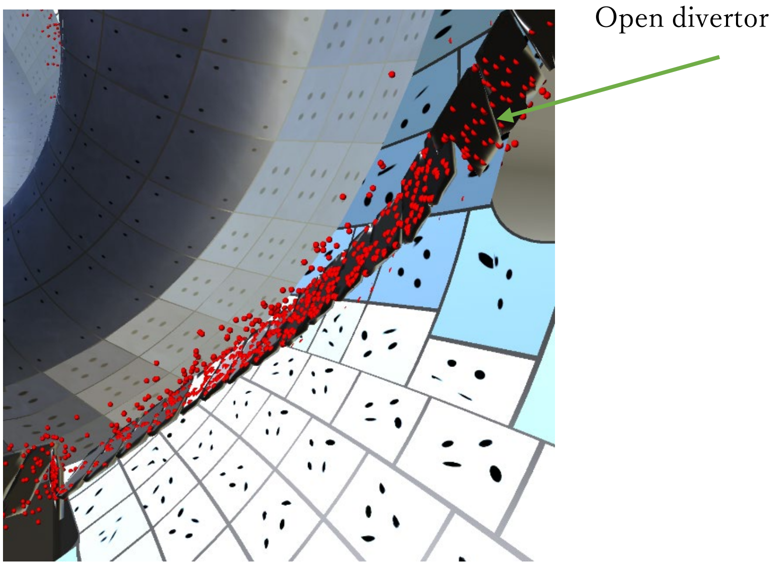


Figure 6. The triton intersection points on the open divertor plates and vacuum vessel wall from the front view.

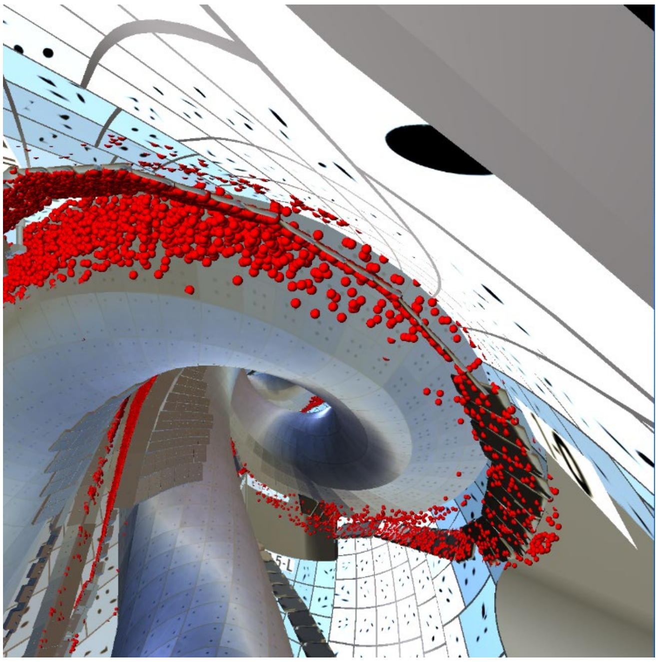


Figure 7. The triton intersection points from the side of the open structure divertor plates.

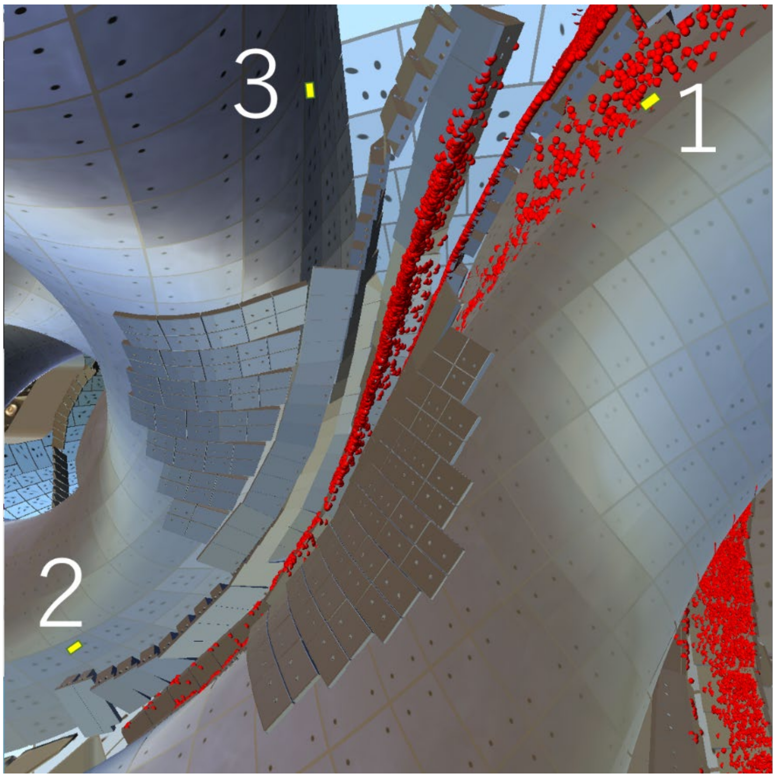


Figure 8. The positions where the probes were set up in fact. Yellow rectangular shows the position.

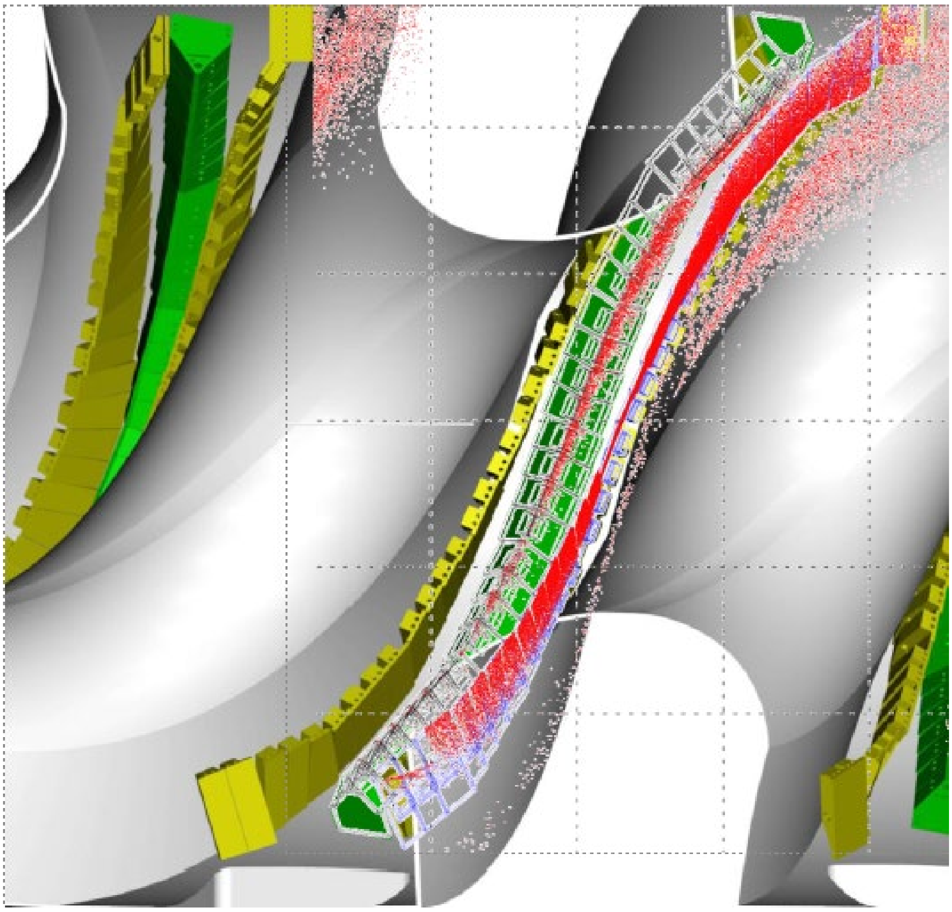


Figure 9. Superimposed figure of the intersection points on the plasma facing wall rendered by CAD software. This figure was made by the experiment scientist, S. Masuzaki. He used this figure for considering where the probes should be installed.

Table 1. Measurement of frame rates

Number of particles	10,000	20,000	30,000
FPS(sec)	36.19	35.76	34.77

Table 2. Evaluation of work efficiency and level of understanding.

	Work efficiency		Level of understanding	
	2D	VR	2D	VR
Experiment scientists	2.0	4.8	2.3	4.8
Simulation scientists	2.4	4.2	2.0	4.6
Graduate students	2.5	5.0	2.5	5.0
Secretaries	2.0	5.0	2.0	5.0
High School students and a teacher	2.2	3.6	2.3	4.9
Total	2.2	4.5	2.2	4.8