

# Visualization of Particle Trajectories in Time-Varying Electromagnetic Fields by CAVE-Type Virtual Reality System

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The particle kinetic effects play an important role in breaking the frozen-in condition and exciting collisionless magnetic reconnection in high temperature plasmas. Because this effect is originating from a complex thermal motion near reconnection point, it is very important to examine particle trajectories using scientific visualization technique, especially in the presence of plasma instability. We developed interactive visualization environment for the particle trajectories in time-varying electromagnetic fields in the CAVE-type virtual reality system based on VFIVE, which is interactive visualization software for the CAVE system. From the analysis of ion trajectories using the particle simulation data, it was found that time-varying electromagnetic fields around the reconnection region accelerate ions toward the downstream region.

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## 1. Introduction

The output data of computer simulations of plasma are generally three-dimensional (3-D) and include several vector fields and scalar fields. As the abilities of computers increase, the data is also getting larger and more complex. It is a significant stage for the simulation researchers to visualize and analyze their complex data to understand what phenomena happens in their simulations. However, it is hard and time-consuming to understand the complex 3-D data, especially vector fields, by using PCs or graphics workstations with usual two-dimensional (2-D) monitors. Such a situation has been increasing year by year. It is why researchers have been looking for new technology and virtual reality (VR) systems, which enable them to visualize and analyze their data stereoscopically, have been used as a visualization tool for numerical data. Among several VR systems, CAVE-type VR system [1] is already recognized as a visualization apparatus and widely spreading. This kind of system has been used in many scientific fields since more than ten years ago from fluid data [2] to archaeological data [3].

We have used the CAVE system to visualize output data of computer simulation of plasma and study collisionless magnetic reconnection, because it is indispensable to analyze the spatial structure of the complex particle orbits and 3-D vector fields in 3-D space by the CAVE system. Collisionless reconnection takes place in the kinetic region where the frozen-in condition is broken due

to the particle kinetic effect. In this region charged particles do not execute a simple Larmor motion but a complex thermal motion called meandering motion [4–6]. It is important to clarify the relationship between ion meandering motion and other physical quantities, such as temperature, in order to understand collisionless reconnection. We developed software for visualizing particle trajectories in electromagnetic fields on snap shot data based on VFIVE [7–10], which is interactive visualization software for the CAVE system [11]. Furthermore, plasma instabilities are also found to be excited in the reconnection region, and influence on the particle kinetic effects by modifying the particle trajectories. Thus, particle trajectories in the time-varying electromagnetic fields are important keys for understanding the role of the particle kinetic effect in collisionless reconnection. For this reason, we have extended the VFIVE to be able to handle time-varying data and visualize the trajectories of particles in time-varying electromagnetic fields. This extension is realized as the animation function to the VFIVE. In this paper, this software extension is reported.

In Secs. 2 and 3, we briefly introduce the CAVE system and VFIVE, respectively. The detail of the software extension is explained in Sec. 4. Application of the software to analysis of magnetic reconnection simulation data is shown in Sec. 5. The performance of VFIVE is evaluated in Sec. 6. We summarize this paper in Sec. 7.

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Fig. 1 CAVE system at Earth Simulator Center, JAMSTEC. The size of screens is  $3\text{ m} \times 3\text{ m}$  each.

## 2. CAVE

The CAVE system is a room-sized immersive system and provides an interactive environment (see Fig. 1). The typical system has four screens, three walls and one floor, the size of which is about  $3\text{ m} \times 3\text{ m}$ . The screens of the CAVE system surround user and display images. The images look stereoscopic while a user wears the special glasses for it. The CAVE system has a head tracking system which is always monitoring the position and viewing direction of the user (exactly speaking, those of the special glasses). Based on the information, the CAVE system is always displaying images which are suitable for the user. To interact with the system or VR space, user uses 3-D mouse called Wand. It is composed of three buttons and a joy-stick. The head tracking system is also monitoring the Wand.

## 3. VFIVE

We have been developing interactive visualization software for the CAVE-type VR system. It is general-purpose and is called VFIVE [7–10]. VFIVE enables users to visualize their numerical data by using basic visualization methods such as isosurface, color contour, volume rendering, field lines, arrows and so on. The CAVE system has three superior features as a visualization apparatus, being stereoscopic, immersive and interactive. We lay big emphasis on the last feature, interactivity, when designing VFIVE. VFIVE builds up interactive visualization and analysis environment in the CAVE system through Wand and does not make the CAVE system “an object viewer”. User can change the visualization parameters, and the change of the visualization parameters is soon reflected in the VR space. For example, when a user changes the isosurface level, VFIVE starts to recalculate the isosurface of new level and show it. VFIVE does not display pre-calculated visualized objects.

The visualization methods can be selected by menu function. By the menu function, a user can select target data and visualization method in the CAVE room. The user

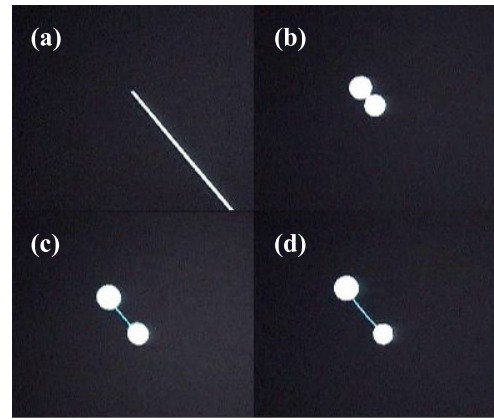


Fig. 2 Graphical user interface of field lines. (a) The laser pointer emitted from Wand is shown. A user can decide the seed position intuitively. (b) When user releases the button of Wand, balls appear at the tip of the laser. (c, d) Two balls start drawing the lines. Runge-Kutta integration begins after user releases the button.

does not have to go out of the CAVE room to select them.

The operations of visualization method such as changing the parameters are easy too. For example, after selecting vector data and field lines, seeds of stream lines can be placed in VR space intuitively. When a user pushes one of the buttons of the Wand, a laser pointer begins to be emitted from it. The user can freely move Wand in his hand and take aim at the point where he wants. When the user releases the button, two balls emerge at the tip of the laser and begin to follow and draw the stream lines (see Fig. 2). The Runge-Kutta integration starts after the user releases the button. Isosurface level can be set by vertical motion of Wand.

VFIVE can handle time-varying data. When a user activates the animation function, VFIVE begins to read data and visualizes it by the same visualization parameter such as isosurface level and seeds of stream lines. The visualized objects such as isosurface are saved as OpenGL’s macro (or polygonal data are saved on a hard disk drive (HDD) when the number of time steps is large). After completing this procedure at all time steps, VFIVE begins to display the visualization objects of each time step one after another.

By the combination of this interactive user interface and the stereoscopic and immersive view, the CAVE system with VFIVE provides 3-D data (or 4-D data) analysis environment to the researchers.

A basic version of this software can be downloaded from JAMSTEC’s web site [12].

## 4. Visualization of Trajectories of Particle

We incorporated a visualization method for trajectories of particles in time-varying electromagnetic fields.

This is based on our previous development [11] and it is for studying ion's meandering motion, which is considered to be related to the collisionless magnetic reconnection mechanism [4–6, 13]. It was reported that drift kink instability (a low-frequency electromagnetic instability) was excited in the reconnection region [14, 15], and that it played an important role in breaking the frozen-in condition for electron [16]. Thus it is necessary to analyze particle trajectories, which pass near the reconnection region in the time-varying electromagnetic field.

In this method, Newton-Lorentz equations

$$\begin{aligned}\frac{d(\gamma\mathbf{v})}{dt} &= \frac{q}{m} \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right), \\ \frac{d\mathbf{x}}{dt} &= \mathbf{v}, \\ \gamma &= 1 / \sqrt{1 - (\mathbf{v} \cdot \mathbf{v})/c^2},\end{aligned}$$

where  $c$  is the light speed,  $m$  and  $q$  are the mass and charge of particle respectively, under a periodic boundary condition along  $z$  direction and an open boundary along  $x$  and  $y$  are solved to calculate the trajectories of particles in time-varying electromagnetic fields. The same graphical user interface (GUI) as field lines described in the previous section is used for placing the seeds of the particle trajectories. There is a big advantage in using the CAVE system with VFIVE in this point because it is much easier to place the seeds near the reconnection region than using usual visualization software with 2D monitor and mouse. As mentioned above, VFIVE can handle time-varying data. This method is linked with the function. The procedure is as follows.

- (i) First of all, user prepares time sequential data of electromagnetic fields, flow velocity, temperature and so on, which are the result of simulation and put all of them onto a HDD. The time interval of storing them onto a HDD should be enough short compared to the characteristic time of the target phenomena to ensure the valid trajectories. In the case of investigating ion trajectory it should be sufficiently shorter than the inverse of the ion cyclotron frequency  $\omega_{ci}$ , for example.
- (ii) User selects this method and places the seeds (initial conditions) of particle trajectories intuitively in the CAVE room by the GUI. The initial position is instructed by Wand, and initial velocity is determined by flow velocity, which is simulation data.
- (iii) User activates the animation function.
- (iv) VFIVE reads the data set of the current and the next steps, including electromagnetic fields placed on a HDD in advance.
- (v) VFIVE solves the Newton-Lorentz equations with linearly interpolating the data of fields between the two steps and stocks the calculated positions in memory. The spatial interpolation is third-order and second-order leap-frog integration is adopted in the calculation. If another visualization method is also

used, visualizations with the same parameters are carried out, and the polygonal data are saved.

- (vi) Back to (iv) till the last time step.
- (vii) VFIVE starts to display the trajectories which look growing as the time step advances, in the CAVE with other visualization objects if any.

In this animation function, the time interval of storing the time-sequential data  $\Delta T$ , that is, updating the polygonal data in 3-D world, and the time-steps  $\Delta t$  of time integration of Newton-Lorentz equations and simulation can be decided independently one another. If they are equal to one another, then updating the polygonal data in 3-D world is performed at the same time as integrating the Newton-Lorentz equations in procedures (iv) and (v), and it is possible to trace particles in 3-D space by the same time step as the simulation. To reduce the amount of stored field data onto a HDD, it is practicable to make  $\Delta T$  larger than  $\Delta t$  as shown in Sec. 5. Needless to say,  $\Delta T$  must be fully smaller than the characteristic time of the target phenomena as mentioned in procedure (i). In this case, integrating the Newton-Lorentz equations is performed several times using the interpolated field data while the polygonal data are updated one time in the procedures (iv) and (v).

By this method, a user can observe the trajectories of particles growing slowly in the CAVE room. In addition, VFIVE's other visualization methods are also available. If VFIVE displays visualization objects such as isosurface and color contour of density when the user activates this method, VFIVE shows the growing trajectories with the time-varying isosurface and color contour of density simultaneously. In short particle trajectories and other physical quantities, which changes in time can be analyzed simultaneously in 3-D space.

## 5. Example of Visualization

As an example of this method, we visualized our collisionless magnetic reconnection simulation data and drew trajectories of ions in time-varying electromagnetic fields. All of the visualized field data are obtained by the three-dimensional PArticle Simulation code for Magnetic reconnection in an Open system 'PASMO' [17–19]. The simulation parameters are as follows: The total number of particles is 143.36 million at initial stage, the simulation box size is  $254\lambda_D \times 127\lambda_D \times 192\lambda_D$ , the scale length of current layer is  $20\lambda_D$  at the initial time, the thermal velocities of electron and ion are  $0.276c$  and  $0.0276c$  respectively, where  $\lambda_D$  is Debye length, and  $c$  is the speed of light. The mass ratio of ion to electron is 100 and the driving field is  $-0.04B_0$ , where  $B_0$  is a constant. The initial condition is given by a one-dimensional Harris-type equilibrium, in which the magnetic field is parallel to the  $x$ -axis and a function of  $y$ -coordinate. At the upstream boundary ( $y$  boundary) ions and electrons come into the system by  $\mathbf{E} \times \mathbf{B}$  drift due to a driving electric field, while at the downstream boundary ( $x$  boundary) particles go out from and come into

the system under the free boundary condition.

The seed points were placed by the GUI intuitively. The time-step  $\Delta t$  of time integration of Newton-Lorentz equation is the same as that of PASMO simulation ( $\omega_{ci}\Delta t = 6.91 \times 10^{-4}$ , where  $\omega_{ci}$  is ion cyclotron frequency). Because the electromagnetic field data are stored by  $100\Delta t (= \Delta T)$ , 98 data of fields are linearly interpolated in the interval  $\Delta T$ . An integration of Newton-Lorentz equation is performed 100 times during  $\Delta T$  with the time-step  $\Delta t$  using the linear-interpolated electromagnetic field data along the time. Figure 3 shows CAVE visualization of the time-varying data at (a)  $T = 0$ , (b)  $25\Delta T$ , and (c)  $50\Delta T$ . The displaying time  $T = 0$  corresponds to the time  $\omega_{ci}t = 40.1$  in the PASMO simulation. The color contour of  $xy$  plane is ion temperature and of  $yz$ -plane is a reconnection component of magnetic field. The blue and white lines are magnetic field and ion trajectories, respectively. A sequence of Fig. 3 shows that the trajectories of ions are growing, that is, ions coming from the upstream boundary ( $y$  boundary) execute meandering motion and go out from the downstream boundary ( $x$  boundary) [4–6, 11, 13]. It is observed that other quantities are also changing. It is found that drift kink instability is excited near the central region in Fig. 3 [14, 15]. It is easy by Wand of CAVE system to instruct the initial positions of particles intuitively in 3-D VR space. It is important to watch the complex structures of particle trajectories and magnetic field from the various view points to understand them, and it is straightforward by CAVE system to observe them in such a way. It is disappointing to project 3-D objects in the VR space on the 2-D picture such as Fig. 3 in order to put the image on the paper.

Figure 4 shows (a) stationary or one-time-snapshot data and (b) time-varying data cases, respectively. In the case of (a), an ion trajectory is calculated and drawn from the upstream boundary under the stationary electromagnetic field data at  $\omega_{ci}t = 36.7$ , while in the case of (b) it is calculated from the same initial position as the case of (a) over a time interval  $36.7 \leq \omega_{ci}t \leq 42.3$  (over the displaying time interval;  $0 \leq T \leq 82\Delta T$ ), and the result at  $\omega_{ci}t = 42.3$  with the calculated ion trajectory during the time is shown in Fig. 4 (b). By comparing between them, the trajectories in time-varying and stationary electromagnetic fields are surely different. In the case of time-varying fields, ions move faster toward the downstream region ( $x$  boundary) from the center region, where magnetic reconnection takes place, than the case of stationary fields. This difference indicates that the time-varying electromagnetic fields, that is, plasma instabilities excited around the reconnection region accelerate ions toward the downstream region. In our previous paper [11] and another paper [20], the trajectory of test particle was investigated in the time-fixed field. We are now investigating detail effects of time-varying electromagnetic field on particle trajectories. To understand the reconnection mechanism, it is necessary to consider it in the time-varying electromagnetic field more carefully.

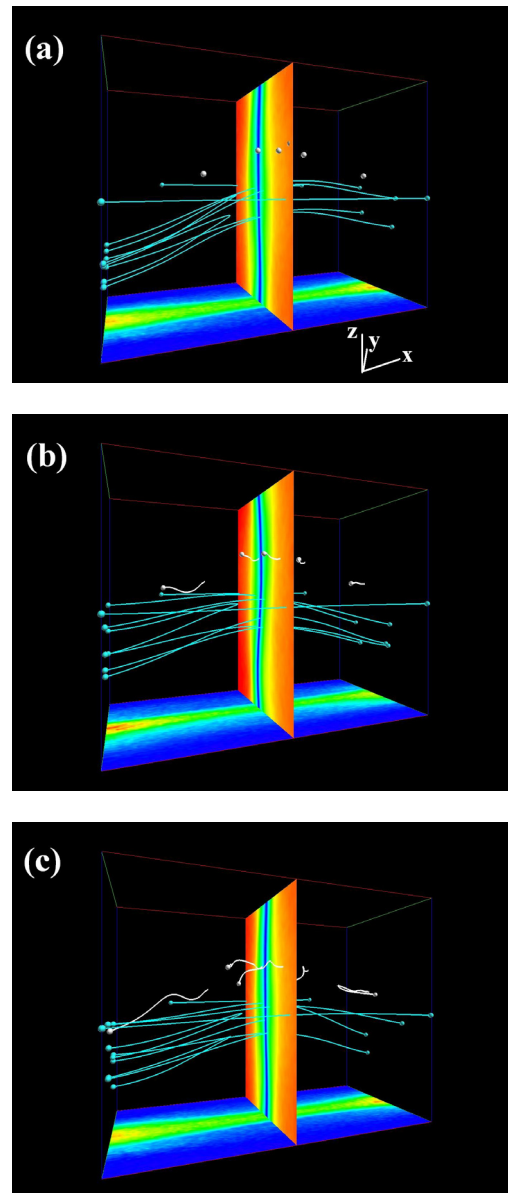


Fig. 3 CAVE visualization of the time-varying data at (a)  $T = 0$ , (b)  $25\Delta T$ , and (c)  $50\Delta T$ , where  $\Delta T$  is time interval of storing the simulation data. The color contour of  $xy$  plane is ion temperature and of  $yz$ -plane is a reconnection component of magnetic field. The blue and white lines are magnetic field and ion trajectories, respectively. The magnetic field lines are drawn by the data at the each time, while the ion trajectories are shown as time-tracing lines from  $T = 0$ .

## 6. Performance of VFIVE

Frame rates and number of polygons were measured for performance evaluation of this software. The CAVE system in JAMSTEC and the same data as Sec. 5 were used. The graphics workstation of this system has eight CPUs (AMD Opteron 8224 SE), 256 GB memory and two NVIDIA Quadro PLEX 1000 Model IVs. The resolution of one screen is  $1050 \times 1050$ .

We measured frame rates in the following three cases:

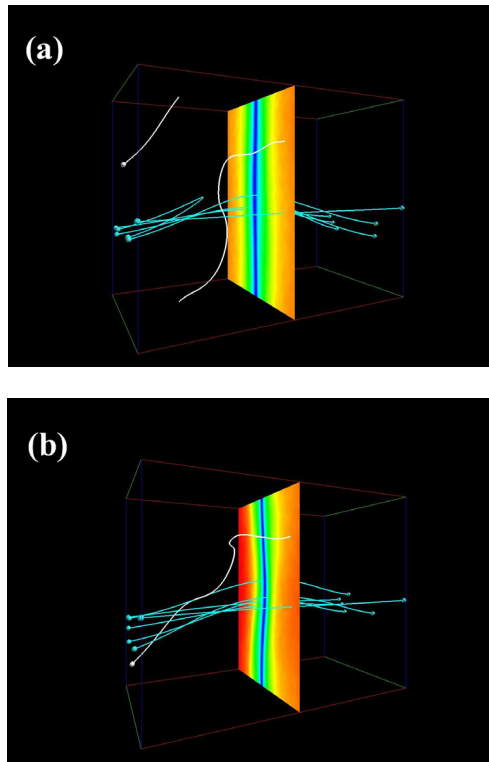


Fig. 4 CAVE visualization of (a) stationary data at  $\omega_{ci}t = 36.7$ , and (b) time-varying data after calculation over a time interval  $36.7 \leq \omega_{ci}t \leq 42.3$ . The start point of ion time-tracing trajectory (white line) is located around the center of upstream boundary ( $xz$ -plane), and the white ball is the final point of the trajectory. The blue lines are magnetic fields at that time.

(1) tracing 20 magnetic field lines, (2) tracing 20 ion trajectories in the constant electromagnetic field, and (3) tracing 20 ion trajectories in the time-varying electromagnetic field. In all cases, two contour slices are displayed simultaneously like Fig. 3. The results are: (1) from 80 to 114 frames per second (fps), (2) from 50 to 60 fps, and (3) from 4 to 10 fps. When these frame rates were measured, the graphics workstation computes the orbits by the integration and displays them simultaneously. After the integration, in other words, the graphics workstation only displays the orbits, the results are almost 114 fps in all cases. Note that the maximum frame rate of this CAVE system is 114 fps.

We also measured numbers of polygons after the integration. The number of polygons of two contour slices is about 33,000. The number of line segments of a magnetic field line is about 4,700, that of an ion trajectory in the constant field is about 12,000 and that of an ion trajectory in the time-varying field is about 30,000. A magnetic field line is displayed with two balls and an ion trajectory is with a ball. A ball is drawn by 64 polygons. The numbers of line segments are the averages of 100 trials (fps and the number of polygons were measured separately). Therefore the estimated numbers of polygons are: (1) 35,560

polygons and 94,000 line segments, (2) 34,280 polygons and 240,000 line segments, and (3) 34,280 polygons and 600,000 line segments.

For current graphics hardware rendering above number of polygons are not a hard job. In cases of tracing ion trajectories frame rates are slowed down during the integration. However, after the integration they recover to almost the maximum value.

## 7. Summary

By adding the method for visualizing the trajectories of ions in time-varying electromagnetic fields to VFIVE, researchers can investigate the relationship between the trajectories of ions and other physical quantities in the CAVE room interactively and intuitively. The trajectories of ions in time-varying electromagnetic fields are different from that in the stationary electromagnetic data. To understand the phenomena, it is surely more important to analyze the trajectories in time-varying fields. We believe that this development will enhance the study of the phenomena in high temperature plasma such as collisionless magnetic reconnection.

In addition, with remodeling the method a little, VFIVE will be able to trace the particle in the time-varying velocity field. There must be lots of applications.

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