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Exploring Plasma Physics Simulations with Virtual Reality

Sofia Pinho David Brás Nuno Verdelho Trindade Alfredo Ferreira João Madeiras Pereira
INESC-ID, Instituto Superior Técnico, Universidade de Lisboa
Lisbon, Portugal
{sofia.pinho, david.bras, nuno.verdelho.trindade, alfredo.ferreira}@tecnico.ulisboa.pt jap@inesc-id.pt

***Abstract*—Simulations in plasma physics generate intricate, three-dimensional datasets that require advanced visualisation tools for meaningful analysis. Traditionally, these datasets are represented and examined using two-dimensional methods on flat screens, which restrict spatial comprehension, a critical aspect of this field. Virtual reality (VR) offers a promising alternative to conventional techniques, improving depth perception and spatial awareness. This demo presents *PlasmaVR*, a proof-of-concept VR tool designed to visualise and explore plasma physics simulation data. The tool supports immersive multidimensional exploration of particles, scalar fields, and vector fields, providing researchers with a more intuitive and comprehensive analytical experience.**

***Index Terms*—Virtual Reality, Immersive Visualisation, Scientific Visualisation, Plasma Physics**

I. Introduction

The Group of Lasers and Plasmas (GoLP)[1] is a research group at Instituto Superior Técnico (IST) dedicated to advancing the fields of plasma physics, advanced photonics, and computational science. GoLP addresses key challenges such as extreme matter behaviour, compact plasma-based particle accelerators, and fusion energy. To tackle these challenges, a combination of theory, simulation, and experiments is fundamental. Plasma behaviour is primarily analysed through computer simulations, allowing for controlled investigation of complex dynamics. Traditionally, GoLP has relied on 2D visualisations to represent simulation results, but these methods fall short in capturing the full complexity of plasma, a dynamic three-dimensional phenomenon. As simulations become more intricate, advanced visualisation techniques are increasingly essential to better understand plasma behaviour.

Despite some existing tools providing 3D visualization of simulations of plasma dynamics, they mostly use traditional interaction paradigms. Recognition of the limitations of conventional visualisation methods motivated the development of *PlasmaVR*. This tool was designed to visualise and interact with plasma simulation data in an immersive 3D environment. As a work in progress, it represents an ongoing effort to address the challenges of plasma physics visualisation, taking advantage of VR. The tool allows users to "step inside" the simulation, providing an intuitive and engaging method to explore complex plasma dynamics. While still under development, *PlasmaVR* already introduces features such as annotation tools, slice tools for cross-section analysis (Figure 1), and interactive controls for manipulating and rotating the simulation, laying the groundwork for future enhancements.

II. Context and Related Work

A. Plasma Physics

Plasma, a state of matter in which a significant proportion of particles are charged, exhibits complex behaviour due to the interactions between these particles, usually electrons and ions, through long-range forces. These interactions give rise to collective motion, waves, and instabilities. To model such systems, advanced computational techniques are required, with Particle-in-Cell (PIC) codes being a prominent example [2]. These codes, such as the fully relativistic and massively parallel *OSIRIS* [3], enable the simulation of plasma dynamics and generate detailed datasets.

Despite the inherently three-dimensional nature of plasma simulations, researchers often rely on 2D visualisations. While some applications support 3D visualisation, they predominantly use traditional interfaces (2D screens, keyboard, and mouse), which lack the spatial awareness and engagement necessary for in-depth analysis This limitation has spurred interest in alternative approaches, such as those using virtual reality, which offers enhanced depth perception and spatial understanding [4]. By immersing users in the simulated environment, VR might provide a unique perspective that can lead to deeper insights into plasma morphology and behaviour.

B. Scientific Visualisation

Scientific visualisation has increasingly embraced immersive technologies, with extended reality (XR) emerging as a key trend across various domains [5], including research studies related to natural, formal, and social sciences [6]. This demonstrates its versatility and potential for enhancing data analysis and user engagement.

In the context of plasma physics, XR technologies have been explored to improve the visualisation of simulation data. For instance, Foss *et al.* [7] developed a system to visualise scalar data from plasma simulations using isosurfaces. Although the system allowed users to observe time-varying data from different perspectives, its interactivity was limited. Similarly,

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[1]https://golp.tecnico.ulisboa.pt/

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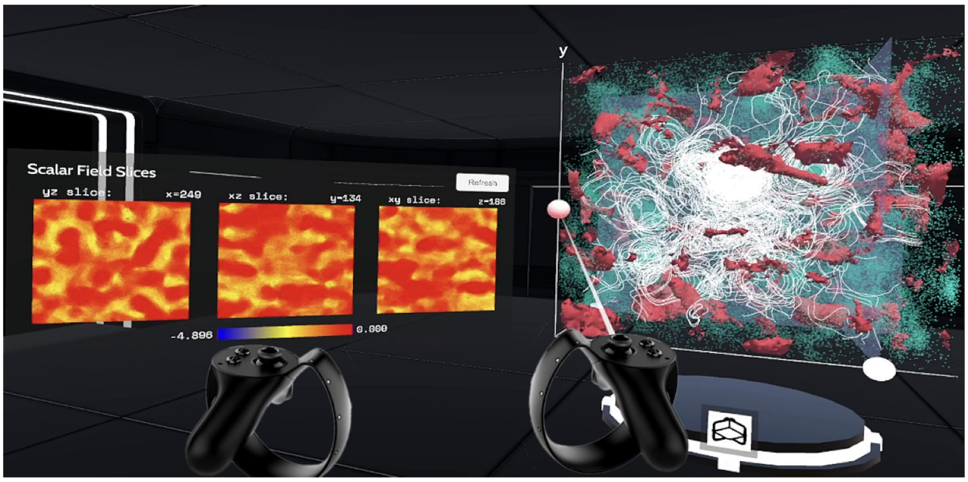

Fig. 1. The immersive environment (mockup) of *PlasmaVR* [1].

Danielová *et al.* [8] proposed a web-based system for visualising plasma simulations, enabling the analysis of particles and fields. However, their approach relied on conventional interfaces, which lack the immersive qualities of VR.

CAVE systems have also been utilised for plasma visualisation, as demonstrated by Ohtani *et al.* [9]. Their work focused on representing magnetic field lines, particle trajectories, and plasma pressure isosurfaces, highlighting the advantages of VR in understanding spatial relationships. Later studies by the same group explored the use of VR for analysing dust particle trajectories in plasma experiments, further underscoring its potential.

Building on these foundations, Verdelho Trindade *et al.* [1] developed a VR platform for plasma physics visualisation, which serves as the basis for this work. Unlike previous systems, this work focuses on the integration of analytical features within a VR-native interface, addressing gaps in usability and functionality. By leveraging the immersive capabilities of VR headsets, this approach aims to provide a more engaging and insightful experience for researchers analysing plasma simulations.

III. PlasmaVR

As stated earlier, *PlasmaVR* is an immersive visualisation tool designed for the exploration and analysis of datasets generated by plasma physics simulations. Initially developed to address the needs of researchers at GoLP, the tool enhances depth perception and spatial understanding of three-dimensional plasma structures. The requirements for *PlasmaVR* were derived from interviews with GoLP researchers, who emphasised the need for dynamic visualisation of particle positions, scalar fields, and vector fields (Figure 2), along with playback controls for animations. Additional functionalities include time-dependent annotation and the ability to slice and segment 3D structures into 2D energy heatmaps.

The system comprises data processing and VR visualisation. Data processing handles the conversion of raw simulation data into a format compatible with the graphical engine used in *PlasmaVR*. This module supports the processing of point clouds, scalar volumes, and vector fields. The VR visualisation manages the rendering of virtual elements and user interactions within the immersive environment.

Upon entering the VR environment, users find themselves in a sci-fi-inspired virtual laboratory. At the centre of this space, a plasma structure is displayed on a platform, where it can be animated, rotated, resized, sliced, or annotated. Users can move inside the plasma structure, and examine its intricate morphology in detail.

A floating panel, accessible via VR controllers, provides access to *PlasmaVR*'s features. This panel includes controls for playback, slicing, rotation, resizing, annotation, and environment configuration. The playback feature allows users to play, pause, or navigate through the animation timeline, enabling precise observation of plasma dynamics over time.

For detailed analysis, users can rotate and resize the plasma structures through a virtual hand mechanism. A sphere appears in place of the controller, serving as a proxy for the 3D structure. By grabbing and rotating the sphere, users can manipulate the plasma structure with three degrees of freedom.

Additionally, *PlasmaVR* incorporates a slicing feature designed to facilitate in-depth data analysis. Users can manipulate handles that control intersecting planes that bisect the structure.The position of each plane defines the cross-sections extracted from the plasma. A 2D panel simultaneously displays the energy heatmaps corresponding to these sections. This real-time, multiaxial visualisation enables researchers to observe and document variations in energy values across the plasma fields.

Annotation in *PlasmaVR* leverages the immersive nature of VR to overcome the limitations of traditional 2D methods.

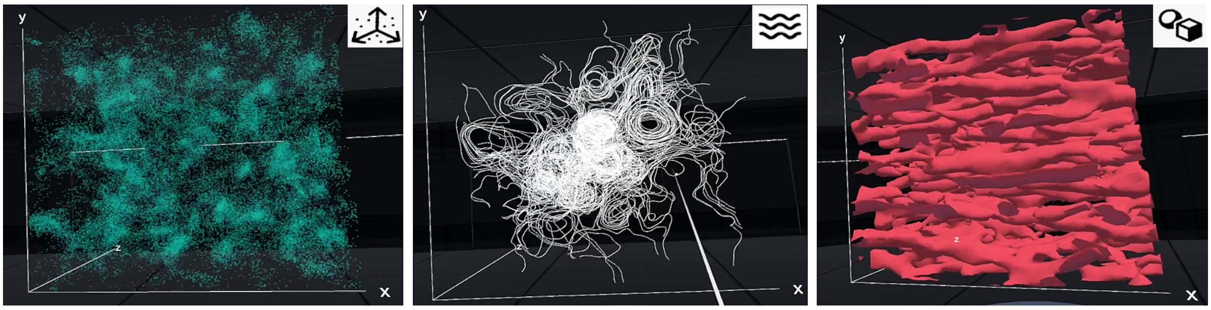

Fig. 2. Particles (left), streamlines (center), and isosurfaces (right) idioms represented in the immersive environment [1]

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Researchers can create precise 3D annotations by drawing directly within the plasma structure, highlighting specific features or anomalies. Annotations can be grouped, customised in colour, and linked to specific time frames, allowing users to track dynamic changes in the plasma structure over time. This capability is particularly useful for documenting complex phenomena, such as the movement of anomalies within the plasma.

IV. Conclusion

This demo presents a prototype tool designed for the immersive visualisation of plasma physics datasets in VR. The tool, which was developed and introduced in prior work [1], provides a multidimensional environment where users can navigate and interact with dynamic, time-dependent representations of plasma structures. It enables researchers to observe morphological changes over time from multiple perspectives, enhancing their understanding of complex plasma dynamics. The tool's architecture, data processing capabilities, and user interface functionalities are described in detail, highlighting its adaptability to raw simulation data.

The current *PlasmaVR* prototype, while demonstrating significant potential for plasma physics visualization, is still a work in progress. Future development will focus on refining its features and expanding capabilities. It aims to create a robust, user-friendly tool seamlessly integrated into researchers' workflows for more efficient and straightforward plasma analysis. We will then perform a comparative evaluation against traditional display methods to identify the benefits and drawbacks of VR in this domain.

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