On the origin of steep radial electric field in the transport barrier at plasma edge

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The solitary radial electric field in the edge of toroidal plasma, which appears in conjunction with transport barrier, is studied based on the electric field bifurcation model. Various nonlinear mechanisms have been pointed out to work [1]. Scaling relation for the solitary structure of radial electric field is obtained [2], and the dependence of the electric field structure on the plasma parameters and geometrical factors is analyzed. Results are applied to tokamak and helical plasmas, for which data with high-resolution have been obtained recently. The order of magnitude estimate for tokamak plasma is not far from experimental observations [3,4], and the case of helical plasma [5] is also discussed. The implication of the results to the limit of achievable gradient in the H-mode pedestal is also discussed.

The status of quantitative understanding through the quantitative test of various mechanisms with experimental observation on the dynamical response is also addressed.

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On the effect of electron temperature fluctuations on edge heat and particle turbulent transport

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The understanding of heat transport mechanisms in the edge plasma is a major issue of the physics of tokamaks as it determines Scrape-Off Layer (SOL) decay lengths and consequently power loads on the divertor targets. Although the mechanisms driving this transport are not yet fully understood, turbulence is likely to play an important role.

In this work, we use the 2D fluid code TOKAM2D in its recently developed anisothermal version to investigate the impact of temperature fluctuations on particles and heat transport in the SOL. More specifically, an energy conservation equation was added for electrons, but the cold ions hypothesis is kept. The geometrical capability of the code was also extended to closed flux surfaces in order to study the physics at play at the separatrix.

We first show that the addition of a fluctuating electron temperature field in the model can change drastically the dynamics of turbulence. For example, we observe important changes in statistical moments of density and particle flux fluctuations with a reduction of the skewness and fluctuation level by about 50% in comparison to isothermal interchange turbulence. The phase of pressure and potential fluctuations is also altered, changing from $\frac{\pi}{2}$ in pure interchange turbulence to a phase shift of the order of $\frac{\pi}{10}$. We analyze these results in light of the additional instability driven by electron temperature gradients, the negative sheath resistive instability [1], which acts on top of the well known interchange instability.

Equilibrium profiles and decay lengths are impacted by these modifications of turbulence. However, linear analysis shows that equilibrium gradients are determined by the marginal instability limit of the interchange instability, suggesting that the transport is still mostly driven by the interchange instability. The power e-folding length is typically 3 to 4 times shorter than the density one. Equilibrium profiles also exhibit distinct layers characterized by different decay lengthsl. When moving from the separatrix to the far SOL, one first finds a boundary layer (about 10 ρ_L - Larmor radii - wide), characterized by steep gradients and reminiscent of the narrow feature observed in experiments, a middle layer (20 to 40 ρ_L wide) which presents flatter profiles and finally a third layer in the far SOL where the decay lengths are intermediate. We characterize the turbulence features within each layer and the dependency of this phenomenology with the model parameters. By doing so, we highlight the different turbulent regimes that can be expected in the main SOL and in the private flux region of divertors.

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Efficient Connection of Collisionless Landau Fluid to Collisional Braginskii Fluid Plasma Physics Models*

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The magnetized plasmas of interest in applications to nuclear fusion span a wide range of collisionality. If supplied with enough heating they are typically collisionless in regions of good thermal confinement, yet collisional in regions where the plasma impinges on sufficiently cool and dense neutral matter. The collisional regime is well-described by collisional fluid theory, which assumes that temporal scales are much longer than the collision time and that spatial scales are much longer than the mean free path. The collisionless regime can be treated with Landau fluid models, which use nonlocal integral operators to accurately describe transport in the long mean free path regime for collisionless plasmas. For magnetized plasmas, the analysis is simplified in that only the parallel motion needs to be treated kinetically, but this leads to highly anisotropic closure models. In this work, a Landau fluid closure, which evolves fluid moments including density, parallel velocity, and anisotropic pressure ($n,u_{\|},p_{\|},p_{\perp}$) is derived by using a collisional model that is one moment higher, so that the derivation involves the anisotropic heat flux ($q_{\|},q_{\perp}$). The combination of the collisionless and collisional physics then generates a closure for the final dynamical moment that maintains accuracy across collisionality regimes. If the isotropization of heat flux is neglected in the choice of closure coefficients, the collisional limit is completely determined by the collision frequencies appearing in the Braginskii equations. The 3+1 model includes the anisotropic thermal and electrical conductivities as well as the parallel thermal force and the heat flux generated by relative flows, which must be Onsager symmetric. The resulting plasma physics model is potentially quite useful for describing the edge of magnetized fusion devices.

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Interplay between plasma turbulence and particle injection in 3D global turbulence simulations

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The interplay between turbulent transport and particle injection - by gas puff, Supersonic Molecular Beam Injection (SMBI) or pellet injection - is an open question relevant for several issues of tokamak physics. It is in particular a key question for the understanding and optimization of particle fuelling as it is likely to influence both the efficiency of the particle deposition in the plasma and the impact of the injection on the confinement. For example, experiments in Tore Supra have demonstrated that SMBI triggers a relaxation of turbulence in the plasma which in turn impacts the fuelling efficiency [1]. This raises also the question of the interpretation of turbulence measurements by gas puff imaging to determine in which conditions and to which point the measurement might be perturbed by the puff.

In this presentation, we use the 3D fluid turbulence code TOKAM3X to investigate the response of the plasma to a localized source of particles. TOKAM3X solves 3D fluid drift equations in the edge plasma in a global geometry and thus includes potentially relevant physics such as curvature driven instabilities or safety factor resonances which have been already identified as key players in particle deposition by pellets [2].

For source amplitudes typical of SMBI or pellets, simulations exhibit a strong reaction of the plasma. As one might expect, the particle deposition leads to a local increase of the pressure by a factor of ~2 which drives parallel flows in the plasma. Quasi-sonic parallel velocities are generated by the particle source leading to a poloidal redistribution of the particles. However, the particle deposition also drives localized pressure gradients which destabilize further interchange turbulence on time scales up to an order of magnitude shorter than parallel redistribution can occur, leading to enhanced turbulent fluxes. These fluxes are orientated outwards in the case of low-field side injection and inwards for high-field side injection leading to large differences in the particle deposition efficiency with trends similar to experiments. By switching on/off physical terms in the equations or scanning the q profile, we will analyse and discuss the respective impact of various phenomena in the particle deposition pattern.

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First principle modelling of the interplay between Langmuir probes and edge plasma turbulence

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The understanding of turbulent transport, which largely governs particle and energy fluxes reaching the wall in the edge plasma of tokamaks, is a necessary step towards the evaluation and optimization of the confinement and of the lifetime of plasma facing components. Exhaustive experimental studies have been carried out to measure fluctuations and time-averaged quantities (density, potential, electronic temperature…) in order to characterize the phenomenology associated with this turbulent transport. One of the most widely used tools to realize such measures in the Scrape-Off-Layer of tokamaks are Langmuir probes. However, these probes are active diagnostics and may locally influence the plasma and perturb local turbulence properties.

Previous numerical studies, modelling this probe-plasma interaction by biasing the target plates in the 2D interchange code TOKAM2D, showed that the presence of a probe in ion saturation mode can significantly perturb the plasma beyond its radius, affect the current circulation even non-locally and alter the measured plasma properties [1,2]. In this paper, we generalize these results following 3 axes of study. We first present multi-probe cases with combinations of biased and floating probes (mimicking rake probes) to observe their mutual interactions. Due to their local impact on parallel current circulation, floating probes alone are shown to perturb the density and potential fields in their vicinity. Combined with the biased probes, these perturbations may lead to significant errors (up to 100% in worse case scenarios) on measured particles fluxes. Electronic temperature fluctuations are then taken into account, adding another instability mechanism in the transport model. Results remain in line the isothermal case with the apparition of a vortex, depleting the density and the electron energy around the probe tip. They also exhibit an additional source of error due to temperature fluctuations in potential measurements. Finally, we extend the test case to more-realistic 3D-slab geometries with the help of the 3D fluid turbulence code TOKAM3X [2]. We in particular discuss the closure through the plasma of the current loop generated by the biased probe. While the probe still influences the plasma transport locally, we show that currents, which were forced to loop through the transverse plane in the 2D reduced geometry, develop a 3D complex pattern which tends to attenuate the probe impact on the surrounding turbulent transport. In light of these results, we discuss the conditions in which measurements can be perturbed by the presence of the probe itself.

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Plasma edge simulation with the continuum kinetic code COGENT*

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We describe recent advances in cross-separatrix and other edge-relevant plasma simulatin with COGENT, a continuum gyrokinetic code being developed by the Edge Simulation Laboratory (ESL) collaboration. Work to date has been primarily focussed on a 4D (axisymmetric) version that models transport properties of edge plasmas including the effects of nonlinear (Fokker-Planck) collisions and a self-consistent electrostatic potential. Rcent work has focused on studies of ion orbit loss and the associated toroidal rotation driven by this mechanism. The results of COGENT simulations are discussed and analyzed for the parameters of the DIII-D experiment. Work has also begun on an initial 5D version to study edge turbulence, with initial focus on kinetic effects on blob dynamics and drift-wave instability. We are employing compiler directives and preprocessor macros to create a single source code that can be compiled in 4D or 5D, which helps to ensure consistency of physics representation between the two versions. We also discuss the status and plans for an extension to model snowflake divertors. Finally, we discuss our strategy for generating grids for cross-separatrix tokamak geometry that avoid the metric singularity that occurs with strictly flux-surface-following grids as the poloidal-field null is approached.

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Modeling of ITER edge plasma in the presence of resonant magnetic perturbations

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An H-mode shot of ITER in the presence of resonant magnetic perturbations has been simulated with account of drifts, currents and impurities for the first time with B2SOLPS5.2 transport code. The choice of the shape of the transport barrier and the drop of the transport coefficients inside the barrier are based on the previous experience of the modeling of tokamaks ASDEX Upgrade and MAST [1].

It is shown that for the chosen regime the radial electric field inside the edge barrier region in the absence of RMPs is of the order of the neoclassical electric field as in the modern tokamaks. The impact of RMPs is investigated by switching on of the radial current of electrons and electron heat conductivity in a stochastic magnetic field [2]. Due to the low neoclassical ion conductivity in ITER special numerical methods were developed and used in the simulations: low anomalous values of radial conductivity to be chosen, special treatment of the ion parallel viscosity, acceleration of the convergence by introducing enhanced parallel viscosity etc.

It is shown that the radial electric field can be reversed by RMPs in ITER more easily than in the modern tokamaks due to the lower neoclassical ion conductivity in ITER with respect to the present day tokamaks. The consequences of the radial electric field reversal are discussed.

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Effect of statistical noise on coupled plasma fluid – Monte Carlo kinetic neutrals simulations: investigation based on artificial noise

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Power exhaust is one of the major challenges that future devices such as ITER and DEMO will face. Because of the lack of identified scaling parameters, predictions for divertor plasma conditions in these devices have to rely on detailed modelling. Most current plasma edge simulations carried out so far rely on transport codes, which consist of a fluid solver for the plasma (typically finite volume) coupled to a kinetic Monte Carlo (MC) solver for neutral particles (atoms, molecules). Examples of such tools are SOLPS, EDGE2D-EIRENE, SOLDOR-NEUT2D, and the more recent Soledge2D-EIRENE [1] developed in our team. One of the main difficulties in interpreting code results is the lack of a proper convergence criterion for the simulations, since statistical noise originating in the kinetic MC calculation precludes, for most coupling procedures in use, residuals to reach machine precision. To solve this issue, one should as a first step take a rigorous look at the various types of errors in the simulations, in order to arrive at a cost effective simulation strategy, as shown by a companion paper (Ghoos et al., this conference). Here, we take a different look at this noise related issues, based on our previous works regarding the proper derivation of transport equations from underlying “first-principles” fluid equations [2]. We argue that these two problems share strong similarities, and that what is usually referred to as the steady state reached by a transport code after convergence bears strong resemblance with the statistically stationary state reached by a turbulence code. This allows us to pinpoint how the noise is affecting the problem to be solved, and provides a physical picture of its effects. We highlight the similarities of this situation with current problems in CFD. In order to illustrate these theoretical results, we rely on the neutral fluid model implemented in Soledge2D-EIRENE, to which we add artificial noise aimed at mimicking results from a Monte Carlo approach. This enables comparisons with the noise-free solution. The results are shown to be sensitive to the noise level, but also on the divertor regime. Relations with the results of Ghoos et al. are discussed, and we show that the extra terms resulting from noise are also clearly identified in their analysis.

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Transport barrier formation in edge turbulence simulation with neoclassical poloidal flow damping

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Transport barriers are a common feature in magnetic fusion devices. The improvement in energy confinement provided by the external transport barrier (ETB) formed in H-mode makes it a crucial ingredient in the pursuit of magnetic fusion as a viable energy source [1]. Since its discovery, the H-mode has been the subject of extensive studies, however theoretical understanding of the phenomenon remains unresolved [2], causing substantial uncertainties on the value of the L-H transition power threshold [3]. Additionally, controlling the associated transient phenomena such as edge localised modes (ELMs) [4] or the intermediate phase (I-phase) [5] of the transition/back-transition is necessary to avoid anticipated degradation of the plasma facing components.
In this work, results of flux-driven resistive ballooning turbulence simulations of the plasma edge accounting for neoclassical force balance governing the poloidal flow show the spontaneous formation of a transport barrier above a certain threshold of input power [6]. Accounting for the radial and temporal variations of the neoclassical coefficients as functions of the pressure profile is identified as a key ingredient for allowing formation of the barrier. Dynamical features like relaxations of the barrier above the threshold, and interplay between turbulence, zonal- and mean-flows when crossing the threshold are observed. The relaxations of the barrier above the threshold appear at constant input power, and become less frequent when power is increased. This property partakes in likening such relaxations to type-III ELMs, which have been linked to resistive modes [7].

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Role of “momentum removal” in divertor detachment

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Detachment of divertor plasma has been a hot topic in the divertor studies for more than 20 years. It is important for tokamak reactor projects such as ITER since it allows a reduction of the power and particle fluxes to the divertor target to an acceptable level [1]. It is also very interesting for theoretical studies and challenging for numerical modelling.

A typical manifestation of detachment in experiment is a rollover of the ion saturation current to the target I_{sat} along with an increase of the particle throughput [2]. Accompanied by a significant reduction of the plasma temperature at the target, this implies a reduction of the plasma pressure in the divertor and the appearance of a pressure difference between the upstream and downstream plasma. Simple two-point models [3, 4, 5] attribute the I_{sat} rollover to this pressure difference and hence stress the “momentum removal” – that is, the friction force acting onto the plasma flow – as the cause of detachment. However, particle balance considerations [6] correct this view by identifying the ion particle losses as the primary mechanism responsible for the rollover.

The present paper develops the discussion further. A more detailed analysis of the flow patterns obtained from detachment modelling with the SOLPS4.3 code [7] shows that flow reversal in the divertor is a common feature of the detached plasma and this contravenes a basic assumption of the two-point models. In particular, 2D modelling reveals that I_{sat} rollover can also be obtained even when the momentum transfer from neutrals to ions is switched off artificially. The comparison shows that the primary role of the “momentum removal” is to keep the plasma density downstream high enough to ensure efficient recombination, which is in turn responsible for the reduction of the ion flux to the target.

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Core-SOL modelling of neon seeded JET discharges with the ITER-like wall

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For a full metal device like JET with the ILW, impurity seeding is an essential technique to reduce the power load to the targets, via enhanced edge radiation. Among quite a number of experiments recently carried out at JET to implement impurity seeding scenarios, two series of pulses have been selected for a thorough study of the main transport and radiation features of neon seeding discharges. Both experiments were performed with vertical target configuration, at low and high delta, at Ip= 2.5 MA and Bt = 2.7 T.

At high delta, the D puffing rate as well as the auxiliary heating power was kept constant (at about 23 MW), while the neon seeding rate was increased pulse by pulse. This leads not only to the increase of the total radiated power but also to the increase of the ratio between the radiated power in the SOL (P_{rad}^{SOL}) to the radiated power in the core (P_{rad}^{core}). (Please, note that, from bolometric signals, the core radiation is predominantly emitted at the edge of the confined plasma). For low delta, the auxiliary heating power was increased from about 21 MW to 28.5 MW, leading to the increase of P_{rad}^{core}, at nearly unchanged radiated power fraction (*frad*). Numerical simulation of these discharges is being made in view of clarifying the main transport and radiation mechanisms of neon seeding at JET.

For the simulations we have used COREDIV code, which self-consistently couples the plasma core with the plasma edge and the main plasma with impurities. In particular, the code has proved its capability of reproducing the main features of the core as well as of the SOL JET discharges both with carbon and with the ILW [1]. Production as well as flushing out of W due to ELMs is not accounted for in the model. Indeed, a steady state W sputtering source is "simulated" in the presently used steady-state version of COREDIV. In fact, an "*ad hoc*" increase in COREDIV of the W yield by a factor of about 1.5 is sufficient, for the most common ELMy discharges, to lead to a good match between calculated and time-averaged experimental W fluxes and concentrations [2].

Although the work is ongoing, preliminary results suggest *i)* the increase of core radiation with increasing input power appears to be caused by larger W thermal sputtering while *ii)* the increase of the ratio of P_{rad}^{SOL} to P_{rad}^{core} with increasing Ne seeding might involve changes in main plasma recycling, possibly due to changes in SOL perpendicular transport and/or edge density, as will be discussed in the paper.

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* *see the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.*

Modelling of impurity transport and plasma-wall interaction in fusion devices with the ERO code: basics of the code and examples of application

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In magnetic confinement fusion devices plasma-wall interaction is one of the key issues in present research. Erosion of wall material and subsequent re-deposition determines the life time of wall components and long-term tritium retention due to co-deposition. Both effects have to be minimised in future devices, such as ITER, to ensure their availability. Thus, understanding and modelling of the involved physics is important. For this purpose, the 3D Monte-Carlo code ERO [1] has been developed.

The basic processes of plasma-wall interaction and impurity transport considered by the ERO code will be discussed and their implementation into ERO will be explained in the present contribution. As an application the sputtering of tungsten and subsequent prompt re-deposition will be addressed. Tungsten is foreseen as divertor target material in ITER and therefore its net erosion is important with respect to life time. Prompt re-deposition of tungsten is expected to decrease the net erosion significantly. To study the amount of prompt re-deposition, ERO simulations have been performed for various plasma conditions. The simulations consider friction and thermal force, anomalous diffusion, and electric and magnetic fields. It is seen that 100% prompt re-deposition can be achieved for very high electron densities (larger than about 10^{14} cm^{-3}) in combination with plasma temperatures larger than about 10 eV. Whereas the impact energies of returning tungsten ions normally correspond well with the energy gained within the sheath potential (~$3ZT_e$), significantly larger energies are seen at small electron temperatures (less than 10 eV) together with high densities (around 10^{15} cm^{-3}). At these conditions the tungsten ions are accelerated efficiently via Coulomb collisions with the background plasma ions flowing to the wall. Possible consequences with respect to an avalanche effect due to self-sputtering will be discussed. The results from the ERO calculations will be compared with simple estimations based on analytical formula [2] as well as recent Monte Carlo [3] and PIC [4] simulations.

Finally, the effect of prompt re-deposition of tungsten will be analysed further under plasma conditions expected for the divertor of ITER. For this, ERO simulations are done for the divertor plates of ITER using plasma parameters calculated with the B2-EIRENE code. It is seen that the high electron densities together with the closed nature of the divertor lead to overall tungsten deposition at the divertor plates near to 100%.

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Effect of PFC recycling conditions on JET pedestal density dynamics

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There is experimental evidence that the pedestal dynamics in type-I ELMy H-mode discharges in a metallic environment (e.g. the JET ITER-like wall) is significantly affected by the instantaneous change in the recycling conditions at the tungsten plasma-facing components (W-PFCs) after an ELM-crash [1,2]. Over the recent years much understanding was gained on the trapping-mechanism of energetic hydrogen-like particle in pure or deposited W-PFC that includes first principles DFT calculations on super-saturation [3].
By employing a heuristic approach, the physical processes leading to formation and release of finite fuel reservoirs in W-PFCs such as near-surface and deep-material implantation and prompt outgassing of particles from PFCs have been implemented in the EDGE2D-EIRENE edge plasma-PWI code. The integrated code JINTRAC (a combination of EDGE2D-EIRENE with the 1D core/pedestal code JETTO) which is capable to model the JET-ILW ELM dynamics [4] has then been adapted to validate the hypothesis that the pedestal fuelling capacity, i.e. the total number of particles transported through the edge/SOL to refuel the pedestal between ELMs, can be strongly affected by localized change of the recycling on the W-PFC wetted area during the ELM-cycle. It is shown that the pedestal performance in terms of ELM frequency and confinement (and hence the core plasma performance) can be adjusted, firstly, by choosing appropriate quantities describing the W-PFCs surface fuel reservoir capacity of the order of 10^{20} particles in the JET divertor, and secondly, by prescribing an effectively reduced recycling coefficient across the ELM wetted area during the ELM cycle.
The modelling results have been compared against the well diagnosed data set retrieved from the C30C JET campaign [5], with the main result, that a delay in the density pedestal build-up after an ELM-crash can be provoked by reduced recycling during the fill-up phase of previously emptied PFC particle reservoirs. A caveat of the model is that the pedestal temperature evolution is barely affected by the change in recycling parameter during the ELM (suggesting that a reduced pedestal heat transport after the ELM must also be present [2]). Another caveat is the missing deep layer out-diffusion (hot particles with E_{kin}~T_{ped} can be deposited deeply in the W-PFCs >100nm depth) which was so far neglected and hence a secondary peak in the D_α light and the saturation current signals normally seen 10ms after the ELM in JET is not yet reproduced. We propose a combination of a 1D reactive-diffusive model (to describe the fast outgassing process of deep layer retention in W-PFCs) with plasma-neutral boundary codes (the EIRENE-part), thus treating the particle reservoir balance in W-PFCs properly into account.

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Visualization of dust particle data with plasma simulation results by virtual-reality system

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Dust is one of the important key factors in determining the confinement profile of fusion plasma. The stereoscopic fast framing cameras were installed in Large Helical Device (LHD) in order to observe the three-dimensional (3D) trajectories of dusts. The 3D positions of the dust particles are recorded as time-sequence data by using the stereoscopic image data [1]. It is useful to watch the 3D trajectories by the virtual-reality (VR) system to understand the 3D structure or the relationship between the trajectories and the other physical valuables, such as the magnetic field line, because the VR system can give a user a deep absorption into the VR world by stereo-view system, tracking system and so on [2]. We make an interface of reading the data and a function visualizing the dust trajectory in the VR space, and implement them to the VR software, Virtual-LHD [3]. Virtual-LHD calculates and visualizes the isosurface of plasma pressure, a streamline of magnetic field and the trajectory of the drift particle in an equilibrium LHD plasma simulation results by HINT2 codes [4,5]. The dust positions are shown as balls by point-sprite method [6], and the trajectories are displayed as several different colored lines to identify each trajectory. Figure 1 shows an example of the VR visualization of the dust particle trajectories with the equilibrium magnetic field line. We will discuss the effectiveness of this system for fusion plasma science.

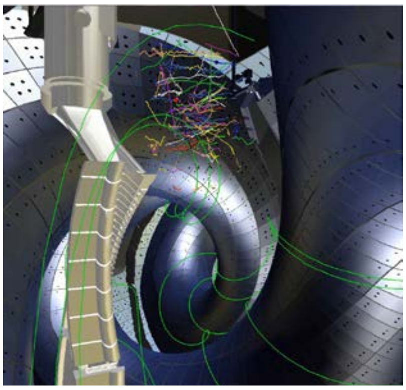

Figure 1: VR visualization of dust particle trajectories and magnetic field line (green).

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[6] For example, see http://marina.sys.wakayama-u.ac.jp/~tokoi/?date=20060227