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Kinetic Model of the Transition Layer between the Plasmas with different Values of Invariants

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Abstract.

The model for the transition layer between the plasmas with different characteristics is important in various physical applications, such as the transport barrier formation in the tokamak plasma, the magnetosheath - magnetosphere transition layer, some astrophysical problems…

These nonlinear structures of matter and the electromagnetic fields could appear as the attractors of a turbulent dynamics of a physical system that has been verified in direct numerical simulations of the dynamical problems.

Conservation of the plasma integrals and invariants is important feature of particular problems and, in some cases, could restrict the mixing of different plasmas, that has been shown in some configurations of the magnetosheath - magnetosphere transition layer in Earth magnetosphere. Four fluid compressible Electron Magneto HydroDynamic (EMHD) model could explain this phenomenon both qualitatively and quantitatively, as it has been reported at the previous (RUSA-2000) meeting, on the example of plasma structures in the down cusp region of the Earth magnetosphere.

In other cases (upper magnetosphere, tokamak plasma), when the kinetic effect of finite Larmor radius could be important, the **pure kinetic approach** can be used to get, from the first principles of the Poincare invariants conservation, the nonuniform plasma and electromagnetic field distributions at the transition layer. The presentation of this approach is the main purpose of current report.

Particular approach differs significantly from that used previously. In particular, **no preliminary assumption were used** for the distribution function form in the transition layer; **the exact Poincare invariants**, rather than the adiabatic invariants or steady distribution integrals, **are used** in the particular approach. Resulting attractor distribution is found **without any consideration of the transient dynamics** that allows exact conservation of the invariants, which is impossible in most cases of direct numerical simulation due to a presence of numerical viscosity.

Motivation and background.

Our purpose is to describe the inhomogeneous plasma distributions that appear as a result of long time turbulent plasma dynamics. Particular problem exists in many physical applications, such as:

- **transport barrier formation in fusion tokamak plasma**. The barrier could determine the plasma confinement time and, thus, the study of its structure is important;
- formation of the **inhomogeneous plasma structures** that exist at the boundary **of the Earth magnetosphere** and magnetosheath regions as well as in the cusp region during the Solar wind plasma penetration into the magnetosphere. The details of the plasma distribution functions in such structures are very important to explain high efficiency of the **long-wave (kilometric) radiation** of the electromagnetic waves from these regions.

The most complex way of solving this problem is the direct self-consistent numerical simulation of particular turbulent dynamics. It has been done mostly in magneto hydrodynamics models, that restricts the consideration by the case of small Larmor radius in comparison with the scalelength of the structure. It has been shown, for example of the Earth magnetosphere, the quick creation of the current sheets of singular width in the magneto hydrodynamical model {Ma}, because this model has not any characteristic scalelength like the skin layer length or Larmor radius. But, both in the transport barriers in tokamak and in the upper magnetosphere of the Earth, the Larmor radius of the ions is of the order of the scalelength of the structure. The hybrid models with the kinetic description of hot ions could be applied in this case. But the simplifications made on this way restrict the consideration by the Maxwell distributions of ions{Lee,Roth}, which is incorrect for the Earth magnetosphere structures, for instance. The largest disadvantage of the dynamical models above is the impossibility to conserve the plasma invariants of motion during the long time of the evolution. Indeed, for the case of the Earth magnetosphere, the collision time exceeds few hours, which is much larger than the time of the plasma structure creation itself. It was found, for instance, that the resulting plasma profiles in the magnetosphere have the additional broadening due the presence of numerical viscosity. In turbulent tokamak plasma, the characteristic time of particle mixing is also quite small, which is verified by the quick (nonlocal) plasma response to the external perturbations.

In a more direct and simple approach, the plasma invariants, such as the adiabatic invariants, the frozen in field invariants are considered to be conserved during the transient turbulent dynamics period of the inhomogeneous plasma structure formation. Then, the universal (canonical) resulting plasma distributions could be restored from the uniform spatial distribution of the plasma invariants. This is the main idea of the global Turbulent EquiPartition (TEP) method, which we have applied, in the semi-kinetic approach, for the tokamak plasma previously. On this way we have got the following results:

- profiles of the plasma density;
- profiles of both the electron and ion temperatures;
- profiles of radial electric fields;
- profiles of plasma rotation;
- equilibrium spectrum and the profile of the turbulent energy level, that could be realized into the waves during the TEP relaxation to the marginally stable distribution.

The knowledge of the turbulent energy profile allows to determine the turbulent mixing time also, which was found to be consistent with the experimental observations. But we have found also, that, under some conditions, the global TEP distributions has the sharp plasma boundary, similar to that in H-mode. We have found also the development of the negative radial electric field and strong plasma rotation at the plasma boundary in this state. We have calculated the profile of the level of the turbulence energy and found its large reduction near the plasma boundary, which corresponds to the formation of the transport barrier. Obviously, the conditions for the application of global TEP are not valid in this case. Indeed, the global TEP cannot be applied directly to the transport barrier with the weak turbulence level. On the contrary, the local TEP method could be used in this zone, since both the particle and the heat fluxes are conserved inside the narrow transport barrier. Thus, the difference in values of the plasma invariants in the transport barrier could be evaluated. Then, the global plasma distribution can be restored as a **coexistence of different global TEPs,** one is for the hot internal plasma and another is for cold pedestal plasma. The plasma density and the temperature gradients are sufficiently large inside the transport barrier, that provides the reduction of the turbulent diffusion down to the self-consistent level. The knowledge of this level in the transport barrier allows to determine the plasma confinement time.

In the previous example, the coexistence of different unmixed hot and cold plasmas appears as a result of different locations of the plasma and heat sources and the leakage. But such coexistence can appear also in the case of penetration of one plasma into another. Such example exists in the cusp region of the Earth magnetosphere during the period of the Solar wind plasma penetration. In the cusp region, which is located close to the Earth magnetic pole, the magnetic field has almost vertical direction and the Solar wind plasma can penetrate deeply into the down cusp region along the magnetic field direction. This penetration can realized easily only without the reconnection of the magnetic field in the particular collisionless plasma. It has been shown, for example, in the direct numerical simulations for unidirectional magnetic field distribution {Ma, Savoini}. In the case of arbitrary directions of the magnetic field in the Solar wind plasma and the magnetosphere, the reconnectionless penetration has the form of squeezing of the Solar wind plasma toward to the Earth in the plane which is parallel to the unperturbed vectors **B**m and **B**w of the magnetic fields in the magnetosphere and the Solar wind plasmas respectively. Such squeezing may form large scale coherent structures in form of the current sheets in the upper magnetosphere-magnetosheath region. The width of each current sheet is determined by the mass of penetrating plasma, but it cannot be less than the ion Larmor radius and the electron skin depth respectively {Rerraro,Roth}. The width of the current layer is much larger than the Debay radius, which provides the conditions for the development of large potential well of the electric field inside the layer and has been detected in observations.

The magnetic field in the down cusp region is strong enough to apply the magneto hydrodynamics model for the description of the coexisting plasmas. We have used 4 fluid model (the electron and ion fluids for both the magnetosphere and the wind plasmas) to describe the resulting inhomogeneous steady structure in a simplest possible way. In a simplified one dimensional (1D) case the plasma and the fields are described by 10 functions: 4 densities, 4 fluid velocities, the electric field potential and the magnetic field profiles. 4 Euler equations could be written to describe the equilibriums of the plasma species, 2 Maxwell equations describe the electromagnetic fields. Other 4 equations are the expressions for the conservation of 4 frozen in field invariants. The system of these ordinary differential equations can be solved for the appropriate boundary conditions, that gives 2 parametric (total mass of the electron and ion components of the wind plasma) plasma distribution and electromagnetic field profiles. Even such simple consideration gives both qualitative and quantitative explanation for the main observed results, such as

- The conditions under which the plasmas cannot be mixed. This condition, in the case of simplest 1D geometry, is ($\mathbf{B}$m $\mathbf{B}$w)≤0 just due to the fact that, if one will assume such possibility, then the densities of plasma species will not be positively defined everywhere. Under this conditions the particular plasmas push one another like the magnets of the same orientation.
- Creation of the hole of the magnetic field, which is due to the same condition above.
- Creation of the hole of electric potential since the ions of wind plasma can penetrate deeply into the magnetosphere plasma.
- The size of the structure is of the order or larger than the electron skin length.

Application of the kinetic model.

The fluid model cannot be used in the opposite case of large ion Larmor radius, which is in the case of transport barrier of tokamak plasma and the transition layer in the upper magnetosphere-magnetosheath layer. Instead, the Poincare invariants can be applied directly in the kinetic model. **The demonstration of such possibility is the main purpose of this presentation.**

Actually, it does not differ significantly from the approach is used in 4 fluid model. The difference is in the following:

- The Poincare invariants, which are exactly conserved during the turbulent dynamics and could be applied for any inhomogeneity of the electromagnetic field, are used instead the frozen in field invariants, for any group of the particles with the same value of the Poincare invariant. Usage of this invariant allows to calculate both exact profile of the drift velocity of particular group of particles and its "thermal" velocities (the temperatures).
- The Liouville's theorem of the phase volume conservation can be used for any group of particles to get the profile of its density.
- The analogue of the Euler equations is not required since these equations coincide with the condition of the conservation of the Poincare invariants.

Then, the electromagnetic field distribution could be restore again from the Maxwell equations. The self-consistent distribution can be obtained by the method of iterations, starting from an appropriate test profile of the electromagnetic fields. The important thing here is the absence of any *a priori* assumptions for the distribution functions of the plasma species. As a result, the distribution functions have the **anisotropy of the perpendicular (respectively to the magnetic field direction) temperatures**, which is the necessary condition for the development of intensive long wavelength electromagnetic radiation from the particular structures.

The Poincare invariants could be used not only for 1D plasma distributions, but for the real case of current sheaths, that allows to obtain self-consistently the electric field along the particular structure.

As a last comment, we would say that the usage of integral Poincare invariants in numerical simulation is even more simple than the solution of boundary problem for differential Euler equations with unknown internal boundaries.