

# RATIONAL PARADIGM OF PLASMA PHYSICS

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## ABSTRACT

In a series of recent papers we have shown that consideration of plasma ensemble statistics is a senseless enterprise [1-6]. It was pointed that known plasma ensemble studies comprise opposite opinions regarding some physical phenomena and hence cannot help one to approach an objective picture of the plasma physical evolution [1,2]. Meanwhile, an idea of substituting real plasmas by plasma ensembles had exerted a key influence on the formation of current plasma physical theory. The ensemble method underlies the BBGKY plasma kinetics, it is hidden behind any hydrodynamic plasma modeling (particularly, behind the MGD plasma theory), etc. This disposition has forced us to create culture of plasma studies with refrain from an ensemble substitution: its diverse principles are highlighted in papers [1-8]. In this paper we outline the kern of our former arguing and reiterate the basic paradigmatic deductions. Some proposals are formulated of further theoretical studies that are urgent for practice of fusion research.

## 1. INTRODUCTION

Many branches of theoretical physics were created within tradition of *studies of statistics of physical system ensembles*. Particularly, this can be said about *all* the current plasma physical theory. The appear of the given tradition was conditioned by culture of theorizing that was developed in physics at the end of XIX-th century: Theorists tried then to substantiate empirical laws of thermodynamics by means of *a classical analytical mechanics*. Namely, they attempted to unravel the establishing of a heat macrophysics within a microdynamic evolution of *a mechanical system*. (The latter term was advanced in analytical mechanics to denote an object possessing by finite total number of “degrees of freedom” and hence permitting formally the full integration of the respective motion equations.) This path was fraught with insuperable technical difficulties, wherefore single systems were ultimately substituted by probabilistic system ensembles. Speaking figuratively, it was suggested to interpret temperature as some characteristic of “dispersion” of systems in the probabilistic ensemble rather than to associate it directly with the dispersion of molecules (ions, electrons, etc.) in their velocities. It was just the switch to the ensemble statistics that have resulted in appear of *a statistical thermodynamics (mechanics)* [9]. In view of the success of the latter theory, the scientific

community has rather quickly accepted corresponding ideas as a basis for physical theoretical studies. They have exerted an important influence on the development of quantum mechanics, they were successfully applied to problem of electric conductivity of metals, to some items of solid state physics, physics of dielectrics, physics of magnetic materials, *etc.* The highest point in this motion consisted of developing of *a nonequilibrium statistical mechanics* and of *a physical kinetics* [10-13]. It can be ultimately said that during the lapsed century the idea of the ensemble substitution has been gradually recognized as one of the most important conjectures of human genius regarding the concealed microscopic beginnings of macrophysical phenomena in nature. *However, the latter is far not the real case:* Our recent plasma theoretical studies have highlighted the *irrationality* of the ensemble method [1-6]. (With this, we have stated the *uselessness* of plasma ensemble studies and hence, generally, the scientific inconsistency of the nonequilibrium statistical mechanics.)

In the given paper we briefly outline milestones of our former theoretical motion. A special emphasis will be given to our key discoveries, i.e. to the irrationality of the ensemble method and to basic consequences of *an asymptotic* character of perturbation convergence. Besides, we propose some further studies that are important for nuclear fusion research.

## 2. SENSELESSNESS OF PLASMA ENSEMBLE STUDIES

Historically, the formation of traditional plasma physical theory occurred at a time when the ensemble method had factually “conquered” the minds of physicists. According to corresponding culturally conditioned tradition, plasma theorists did always substituted real plasmas by plasma probabilistic ensembles and rendered laws of evolution of the ensemble statistics as true physical laws of the plasma evolution. Sometimes the ensemble substitutions were introduced directly, but generally they entered into theoretical considerations under covers of some plausible assumptions. For instance, through the concept of mean field that underlies the Vlasov equation [14].

It should be stressed that the idea to substitute real plasmas by plasma ensembles roughly contradicts to the common sense. To put aside that it sounds extremely unnatural, the appropriateness of such substitution cannot be rationally justified. Evolution of the ensemble statistics depends on the ensemble content, and hence considerations of varying ensembles can lead to differing final deductions on laws of plasma physical evolution. Generally, the ensemble averaging veils unpredictably the genuine frescos of plasma physical phenomena. We have pointed at a number of plasma phenomena that illustrate these deductions. The most instructive of respective illustrations is the physics of stochastic electron acceleration. In a turbulent plasma, Langmuir waves scatter thermal electrons along direction of their propagation, which results in *nonresonant diffusion* of electrons in their *momentums* and hence integrally in the electron heating. The former common opinion was that this phenomenon cannot violate the conservation of quanta of Langmuir wave field. This opinion was established due to rigorous calculations by Tsytovich [15,16]. But the history of plasma studies knows also other rigorous calculations that comprise an intense wave quanta decay: Plasma thermal electrons are quickly heated at the expense of Langmuir wave energy. This decay results in radical changes in the images of plasma physical phenomena. Particularly, the wave energetic decay is well sufficient for precluding the Langmuir wave collapses. For this reason we have thoroughly analyzed three independent representative series of beam plasma experiments that were formerly assumed to evidence for the Langmuir wave collapse. We have shown that in reality they evidence against the collapses [1-3]. We would like to emphasize that the former common belief in wave quanta conservation does not comply with these experimental plasma observations. On the contrary, deduction of intense wave decay does comply. Meanwhile,

the latter deduction was first formulated even in 1965 but then forgotten: See paper by Bass, Fainberg and Shapiro [17]. It always stood aside the traditional theory because contradicted to its common principles. The latter principles were merely *heuristic* ones; the above studies of Tsytovich had an effect of rescuing them and thus had delayed formation of rational plasma theory.

In such a way, traditional ensemble -oriented considerations of wave dissipation due to the stochastic electron acceleration have highlighted the uselessness of plasma ensemble studies: The ensemble studies cannot help one to unravel objective laws of the plasma macrophysical evolution. The same deduction was confirmed by kinetics of Langmuir wave scatter induced by plasma electrons and also by the evolution of the electron distribution in response to that scatter. Regarding the former we have shown that traditional theory depicts adequately only the scatter of long Langmuir waves, whereas the intensity of the scatter of short Langmuir waves is substantially undervalued compared to a real one [4]. Regarding the evolution of electron distribution during the wave scatter, conceptions of traditional theory veil its real physics in all situations [6].

At this point of our narration it is appropriate to stress once more that the ensemble substitution is embodied in all traditional approaches to plasma description. Let us list and discuss some of them. First, the plasma kinetic theory after Bogoluibov [10] –Born –Green [18] –Kirkwood [19] –Yvon [20]. It was created just within the tradition of ensemble studies, and it is only within the practice of probabilistic ensemble considerations that its key notions, namely multiparticle distributions, possess some sense of consistent statistics. Second, the hydrodynamic modelling of nonlinear plasma phenomena. On a hydrodynamic level of description any real plasma cannot be distinguished from many others with slightly varied positions and momentums of individual plasma particles and hence from many of plasma ensembles. For this reason the degree of correspondence of hydrodynamic model to plasma realities is always doubtful: Hydrodynamic plasma modelling has no much sense. Particular illustrations to this fact are the Zakharov's hydrodynamic plasma model with its prediction of Langmuir wave collapse and the plasma hydrodynamic analysis by Vedenov and Rudakov with its prediction of long-wavelength plasma modulational instability: Both these phenomena are impossible in view of real Langmuir quanta decay [2,3]. Third, Hamiltonian approaches to description of phenomena in a turbulent plasma. They render the plasma as a continuous medium. Naturally, real plasma as a mixture of discrete charged particles cannot be reduced to a continuous medium without the ensemble substitution. The given our list can be continued further on: Many of currently popular activities in theoretical modelling of plasma phenomena are scientifically unsound.

### **3. RATIONAL LOGICS OF DEVELOPING PICTURES OF PLASMA MACROPHYSICAL PHENOMENA**

In view of above highlighted irrationality of the ensemble method, it is necessary to revise the logics of developing the plasma descriptions. A rational theory of plasma physical phenomena should be obtained from a full plasma description, by its accurate reducing. The reader is reminded that the full description of a classical ionized plasma is given by the Klimontovich [21] –Dupree [22] and Maxwell equations and that the integration of the Klimontovich -Dupree equation implies integration of motion equations for all plasma particles. The problem is that the latter is technically infeasible. That is why we speak about the *reducing* of full plasma description: One should disengage himself from data on positions and momenta of individual plasma particles and still depict as better as possible an objective picture of the plasma macrophysical evolution. For natural solution of this dilemma one should study statistics of motions of individual plasma particles in their complicated interaction. That is, starting from the distribution function of

Klimontovich, one should develop some statistically well defined function that does not contain information on spatial positions and momenta of individual particles. It can be said that the transition from full plasma description to the BBGKY kinetics comprised creation of such statistics from the above distribution just by the ensemble averaging. A necessity of avoiding that averaging forces us to substitute it by a properly organized averaging in the phase space of particle positions and momenta. In short, the situation dictates logics of calculations that has nearly nothing in common with the traditional plasma theoretical calculations. It can be characterized as a culture of rigorous developing of plasma kinetic descriptions. The author have created the beginnings of the latter, its diverse aspects are fixed in papers [1-8]. It is not possible to discuss here the essence of our theoretical conceptions in detail. We note only that we have adopted for plasma studies the approaches typical to Wyld diagram technique [23], in its two-time redaction. That is, we have developed some perturbation theory. Note that the reducing of full plasma description do inevitably proceed through some iteration procedure, whether one follows our instructions or keep the logics of traditional calculations. At this field lies the *second* of basic positions that comprise the necessity of substantial changes in the practice of plasma theorizing:

### **3.1 The asymptotic character of convergence of perturbation theory.**

The notion of asymptotical convergence can be clarified as follows. Even if one has some small parameter for perturbation expansion, his expansion will first converge to some optimal order of consideration, but then inevitably diverges. The given property was known rather well in tradition of plasma theory, but its key consequence was not clarified. It can be formulated as follows. One can obtain differing scenarios of plasma macrophysical evolution even with a single perturbation theory, having merely varied the lowest order approximation of his perturbation expansion. Therefore, a problem arises of the most rational choice of that lowest order approximation, otherwise the final theoretical deductions will be inadequate to the objective picture of the plasma macrophysical evolution. We reiterate that this position was not perceived in former culture of plasma studies. Apart from this, the asymptotic convergency of the theory imposes new restrictions on appropriateness of diverse mathematical procedures in derivations of plasma kinetic scenarios. For instance, the traditional ease in temporal Fourier transformations at intermediate calculations should be notably restricted: Use of respective transforms is fraught with the danger of substantial deviation of final deductions from real physics of the plasma evolution. This feature of the Fourier transformation can be commented as follows. None of simplified plasma descriptions can provide scenario of the plasma evolution that never deviate from the real plasma macrophysical evolution. In view of this, the most reasonable goal for theorist should consist of developing the picture of the plasma evolution that approximate as better as possible the current tendencies in real plasma evolution. Respectively, time derivatives of plasma physical parameters in final equations should depend on current plasma state and its nearest past. The remote plasma future and past can be even absent altogether, as is the usual case in the laboratory experiments. Meanwhile, transition from time originals to frequency Fourier transforms supposes an eternal plasma evolution: all periods of that evolution are weighted by the respective transform. That is, theorist supplements an urgent plasma history by arbitrary assumptions on plasma state in remote past and future. Speaking in terms of traditional statistical mechanics, he manually enlarges the entropy in the problem of plasma description. (Note that appeals to Laplace transformations do equally suppose the supplementing of real plasma history by nonexistent plasma states.)

We have clarified above the most important positions that actualize extensive revision of plasma theory. For gaining the convincing power of our argumentation, let us specify a bit more thoroughly the current set of our publicly fixed conclusions.

#### 4. LIST OF ACHIEVEMENTS IN STUDIES OF “SINGLE” PLASMAS

In above narration, the problem of nonresonant electron diffusion in momentums helped us to visualize the irrationality of traditional plasma theory, which in turn inspired us on creating the rational logics of developing plasma kinetic descriptions. Naturally, we have applied our approaches for study of the very nonresonant electron diffusion. Refraining from the plasma ensemble substitution, we confirmed idea of intense collisionless decay of Langmuir wave quanta [1,2].

Development of real physical picture of the collisionless dissipation of Langmuir turbulence has permitted us to discover three important consequences. First, the dissipation impedes the formation of a *Langmuir wave condensate* (see Appendix in Ref. [1]). [The reader is reminded that the Langmuir condensate was believed to form due to the wave scattering induced by plasma particles: waves should have been ultimately transferred to the long-wavelength region of the turbulence spectrum. The puzzle of dissipation of the condensate energy has motivated large body of former Langmuir turbulence studies.] Second, the collisionless wave dissipation prevents the development of Vedenov - Rudakov's long-wavelength plasma modulational instability [3]. (The reader is reminded that corresponding paper by Vedenov and Rudakov, see Ref. [25], was one of the most stimulating plasma theory publications.) Third, collisionless wave dissipation suppresses the Zakharov's short -wavelength plasma modulational instability [2]. This instability was originally rendered as an initial stage of Langmuir wave collapse [24], hence its absence just highlights the impossibility of the collapse initiation. Note that the “collapse science” was a rather opulent branch of former plasma turbulence theory, and its contributors developed pictures of collapse scenarios even without the short –wavelength modulational instability. For this reason we performed thorough analyzes of diverse items of that science and have affirmed the impossibility of collapses in a Langmuir turbulence [3]. Namely, we have

- A) shown the impossibility of wave energy accumulation in plasma density cavities via nucleation [3]. (For the first time the misconception of *nucleation* was advanced by Doolen [26], after one-dimensional simulation of Zakharov's plasma hydrodynamics [24]),
- B) stated inadequateness of modelling the collisionless plasma by the Vlasov equation instead of the Klimontovich -Dupree's one [3]. (Correspondingly, we have developed more adequate understanding of applicability area of the Vlasov equation in plasma considerations. One of its applications that is conceptually acceptable for the nonlinear plasma studies the reader can reveal in intermediate calculations of Ref. [5]),
- C) stated inadequateness of the “Particle in Cell” method of numerical plasma simulation to the plasma nature [3].

It is worthy of reiterating that the concepts of the Langmuir condensate, of the Vedenov -Rudakov's plasma modulational instability and of the Zakharov's short-wavelength plasma modulational instability constituted the kern of the former Langmuir turbulence theory.

In Section 2 we have mentioned our results on wave scattering induced by plasma electrons [4,6]. On the one side, we have shown that the formerly accepted Tsytovich's picture of the phenomenon (see Ref. [27]) undervalued substantially the intensity of induced scattering of short Langmuir waves [4]. On the other side, it was found that corresponding vision of the process does not simply veil the genuine evolution of the electron distribution during the scattering, but entirely distorts its picture [6].

Note also that in Conclusions of Ref. [5] the reader can find a bit more informative outline of generic defects of the BBGKY kinetics as compared to one present at Section 2.

Completing this section, we would like to point at one more phenomenon that highlights importance of our research. It is the suppression of electron heat conductivity during the beam –plasma interaction that was observed on GOL-3 facility (Novosibirsk, BudkerINP) by Burdakov *et al.* [28]. We have commented in Ref. [29] that the corresponding experimental data agrees reasonably with assumption that the characteristic effective frequency of electron collisions in a turbulent plasma  $\nu_{eff}$  is of the order of inverse time of scattering of Langmuir waves on forced plasma density inhomogeneities that was known after Malkin [30]. Noteworthy that extension of Malkin's theory onto the experiments of Burdakov and his colleagues is a rather speculative enterprise. On the one side, Malkin's conclusions are doubtful since he started from Zakharov's hydrodynamic model of plasma phenomena. (Recall our comments regarding the plasma hydrodynamic descriptions.) On the other, the respective theory was oriented on nonmagnetized plasmas, whereas in the experiments on GOL-3 the plasma is magnetically confined. However, currently one can well use the Malkin's inverse time of scattering of Langmuir waves on forced plasma density inhomogeneities as the most consistent estimate of characteristic inverse time of the plasma nonlinear evolution. For completeness of narration we present it here (see Eq. (14) in Ref. [30]),

$$\gamma_{four} \propto \omega_{pe} \left( \frac{W}{nT} \right)^2 \frac{\omega_{pe} (\Delta k c_s) \Delta k c_s}{(\Delta \omega)^2 \gamma_s}. \quad (1)$$

(Here  $W$  is the energy density of Langmuir turbulence,  $nT$  is the plasma thermal density,  $\gamma_{four}$  denotes the inverse time of above four-wave process of wave scatter by forced plasma density inhomogeneities,  $c_s$  is the typical phase velocity of ion sound,  $\Delta k$  is the spectrum width in wavevectors,  $\Delta \omega$  is the frequency width of Langmuir wave spectrum.) Suppose for a moment that the given estimate *overvalues substantially* the real inverse time of the plasma nonlinear evolution. This would have meant that the nonresonant electron diffusion is inefficient, i.e. that the Langmuir quanta do not decay. (The reader is informed that the characteristic inverse time of nonlinear plasma phenomena defines the rate of the collisionless wave dissipation, see detailed discussions of this position in Refs. [1-3].) The latter would have justified hydrodynamic approaches used by Malkin after Zakharov [24] and hence the very Malkin's final result (1). In short, a logical theory of Langmuir turbulence in a “single” plasma is still undeveloped, especially for magnetically confined plasmas, and therefore the Malkin's estimates portray the most consistent of currently existing quantitative understandings of nonlinear phenomena in a plasma with Langmuir turbulence. We clarify here only the following. The above  $\gamma_{four}$  defines conceptually the rate of collisionless wave dissipation. This permits to evaluate more logically an effective rate of the electron collisions  $\nu_{eff}$  that enters kinetic coefficients of plasma transport phenomena. We speak here about the inverse time of thermal electron scatter on an angle of order unity. The latter inverse time should correspond formally to a time of heating plasma thermal electrons on extra plasma temperature, i.e. to a time of obtaining heat  $nT$  by plasma electrons due to the thermalization of the wave energy. The respective time is derived as  $nT / (\gamma_{four} W)$ , where  $\gamma_{four} W$  is the rate of the turbulence thermalization. For this reason

$$v_{eff} \propto \gamma_{four} \frac{W}{nT}. \quad (2)$$

Thus, in Ref. [29] feature  $v_{eff}$  was associated with the very  $\gamma_{four}$  illogically.

We do not intend to reconsider in detail the disposition that was reported in Ref. [29]. The basic statement of that paper was surely correct: Presence of plasma turbulence results in substantial lessening of electron mean free path and hence in substantial suppression of the plasma thermal conductivity. What is about more consistent theory of this phenomenon – its developing should constitute a subject of special studies.

## 5. SOME DIRECTIONS OF STUDIES CRUCIAL FOR FUSION RESEARCH (INSTEAD OF SUMMARY)

Our studies have shown that the former plasma theory cannot adequately depict the nonlinear plasma behavior. Meanwhile, the nonlinear plasma phenomena constitute the basic aspect to be regarded for evaluating potentialities of fusion installations. Let us comment a bit the given statement.

In current practice of developing fusion projects, a large place is occupied by the hydrodynamic plasma modeling and also by the numerical plasma modeling. Note that we have mentioned at the end of Section 2 that hydrodynamic plasma study as a typical plasma ensemble study has no much sense. Equally, in Ref. [3] we discussed inadequateness of the most recognized numerical method, namely PIC method, to the plasma nature: It permits to emulate the “Vlasov” plasma only and by no means the “Klimontovich–Dupree” one. Both the plasma hydrodynamic and the numeric modeling utilize heuristic ideas that were conditioned by cultural traditions of the lapsed century. We stress that each of respective ideas should be subjected to severe checking on its consistency: recall the failure of concept of Langmuir wave quanta conservation. Particularly, this thesis is just applicable to hydrodynamic plasma descriptions. To put aside that they are usually discussed in situations where the plasma cannot be described hydrodynamically altogether, they inevitably exploit some heuristic assumptions on equations terms answering to nonlinear effects.

Take the problem of magnetic plasma confinement. Even if one solves the problem of MGD plasma stability (a linear one!), there remains the problem of evaluation of plasma losses across the magnetic field. On a boundary of plasma volume one inevitably has a gradient of plasma density, wherefore the drift plasma turbulence develops. This turbulence influences on plasma particles; most likely that considerations of corresponding influence following traditional recipes would have undervalued substantially the respective plasma traversal diffusion. The other problem: plasma heating by relativistic electron beams. This heating proceeds through developing of diverse nonlinear plasma phenomena, and proper ideas of their physics would have substantially helped in searches for possible ways of gaining its efficiency. The same can be said about the electron cyclotron plasma heating. On the one side, its efficiency depend on the amplitude of forced electron cyclotron oscillations that depend both on the power of microwave radiation and on the intensity of nonlinear phenomena that the plasma electrons are participating in. Correspondingly, more adequate theoretical images of respective nonlinear phenomena will again help in gaining the efficiency of the heating. On the other side, orientation on more rational conceptions of basic physical notions (e.g. waves) may evoke some new schemes of the heating arrangement, possibly more effective compared to traditional ones.

In view of above portrayed disposition, it is necessary to change radically the existing practice of plasma theoretical studies. Many of former understandings of plasma phenomena should be reexamined; yet more new important understandings will appear

during the respective revision. This job is worth of participation of plenty of theorists. As a *single* theorist, the author invites the reader to join him in following undertakings:

1. To complete creation of logical Langmuir turbulence theory that was initiated in Ref. [5],
2. To develop rational kinetic theory of a nonideal rarefied plasma instead of the BBGKY kinetics,
3. To reconsider understandings of anomalous plasma electric and heat conductivities (of transport phenomena in general),
4. To initiate rigorous derivations of plasma kinetics in external magnetic fields,
5. To study diffusion of a magnetically confined plasma across a magnetic field which diffusion originates from the plasma kinetic phenomena.

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