J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 180–188

A Prospect – Plasma Physics, *quo vadis.*

ITOH Kimitaka*
National Institute for Fusion Science, Toki 509-5292, Japan

(Received: 5 December 2000 / Accepted: 5 October 2001)

Abstract

A prospect of plasma physics at the turn of new century is discussed. The theme of this conference identifies the future direction of the research related with plasmas. Main issue is the potential and structure formation in plasmas; More specifically, structures which are realized through the interaction of electromagnetic fields, in particular that with electric fields, in non-equilibrium state. An emphasis is made to clarify the fundamental physics aspects of the plasma physics in fusion research as well as that in the basic research of plasmas. The plasma physics will give important contribution to the solution of the historical enigma, i.e., *all thing flow*. Having an impact on human recognition of nature and showing a beauty in a law, the plasma physics/science will demonstrate to be a high-quality science in the 21st century.

1. Introduction

The 11th International Toki Conference is organized at the end of the 20th century, focusing on the subject of potential and structure. It shows the achievement where the plasma physics of 20th century has reached, at least in the area of conference topics. Therefore the prospect, which is given at the end of this conference, might imply to provide a perspective of the plasma physics in the 21st century. In the following, an emphasis is made to clarify the fundamental physics aspects of the plasma physics in fusion research as well as those in the basic research of plasmas**.

In some of preceding conferences [1], couples of prospects have been presented. In this prospect, it is intended not to repeat previous ones, owing to the limit of allocated time in the programme. Summarizing this conference is not in the scope of this presentation as well; examples here is limited and might be biased. Such shortcomings would be compensated, if this prospect stimulates readers to access various review articles in order to search thorough descriptions of related work.

2. Beginning of Physics of the 20th Century and Theme of This Conference

When one think about the new century, it is worthwhile to look back how the physics of 20th century has begun. It is well known that Lord Kelvin described the status of the physics of that time as "The beauty and clearness of dynamical theory is obscured by two clouds". These two clouds are the remaining enigma at that time, i.e.,

(1) Motion of the earth through elastic ether

(2) Anomaly of the specific heat ratio of the materials which are composed of molecules.

The specific heat ratio did not agree with the calculation based on the equi-partition law and the Boltzmann statistics. The solutions of these two problems were given by the progresses in the theory of relativity and in the quantum physics. It turned out clear that this is the area where the most picturesque evolution of the physics of 20th century has been made. If the matter is in the

** It is also noted that some of readers might use words 'plasma science' to describe what is called 'plasma physics' in this article. No strong discrimination is intended here between these two phrasings.

*Corresponding author's e-mail: itoh@nifs.ac.jp

thermodynamical equilibrium, its property can be precisely calculated, in present days, by use of the equipartition law with Hamiltonian described by quantum theory.

At the turn of the 21st century, it has become increasingly clear that only very limited part of our universe is in/near thermodynamical equilibrium. Almost all in the universe, of which we have empirical knowledge, is far-away from the thermodynamical equilibrium, full of dynamics that generates structure, and in the *plasma state*. One of the central issue of the physics in the new century is to investigate the law that governs the plasmas in nonequilibrium state.

The theme of this conference clearly identifies the future direction of the research related with plasmas. Main issue of the theme is the potential and structure formation in plasmas. Structures which are realized through the interaction of electromagnetic fields, in particular that with the electric fields, in non-equilibrium state. This is schematically shown in Fig. 1. In this figure, the word 'microscopic structure' means that the focus is placed on the range of the scale length of interaction between particles or elements: (Organized form could be realized in much wider region than the characteristic scale length of binary interactions.) The 'macroscopic' implies that the scale length of concern (e.g., inhomogeneity) is much longer than that of the binary interactions. Combination of the magnitude of the coupling (often represented by the plasma parameter $\Gamma = 1/n\lambda_D^3$) and the distance away from the thermodynamical equilibrium provides the variety in the spatial structure and temporal evolution of plasmas.

In the following, a prospect is discussed, choosing keywords of

Structure and turbulence
Statistical physics
Irreversibility, chaos and control
Symmetry
Momentum transport
Improved confinement
Synergy of research methods

Finally, closing is made discussing Exploring plasma physics.

Readers might stress other important issues in the plasma physics in the 21st century. For instance, the energy release induced by the change of topology, the abrupt change of topology, the acceleration of selective particles, the nonequilibrium atomic and nuclear physics in the plasma state, the gravitational interactions, the gluon plasmas, the matter-antimatter plasmas, etc., are the challenging subjects for the human recognition of the nature. These important issues are not addressed, because this prospect is discussed along the main subject of this International Toki Conference.

3. Structure and Turbulence

One of the main issues is the law of mutual regulation between the global (or mesoscale) structures and turbulence. It has been well known that

(1) turbulence destroys structures.

This has often been discussed in conjunction with the

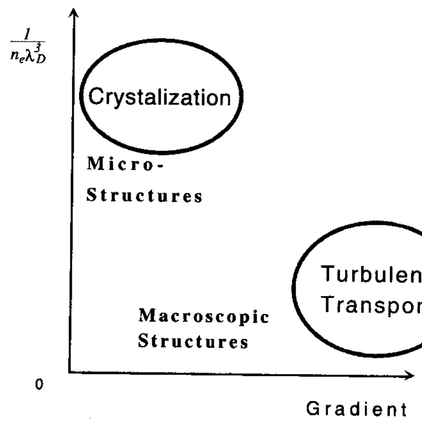

Fig. 1 Direction of research on structures in plasmas

Fig. 2 An example of Karman-vortex-like structure in clouds. Clouds near Kyushu island are shown. (Quoted from [2]).

plasma confinement in toroidal devices. Anomalous transport, which is considered to be induced by the plasma turbulence caused by various instabilities, limits the energy and particle confinement times in toroidal plasmas. In the fusion-related research using toroidal plasmas, the suppression of turbulence has been the main problem in order to make confinement time longer.

It should be emphasized, at the same time, that

(2) turbulence generates structures, and that

(3) it is accompanied by transitions.

In reality, many examples of structure, which we observe in daily life, in laboratory experiments and in observatories, are sustained by the presence of turbulence. If one chooses an example from meteorological observations, a Karman-vortex-like structure of clouds is often found. (See Fig. 2). Karman vortex appears in the range of the Reynolds number about 100. The system of air and water vapor in Fig. 2 has extremely large Reynolds number, and the observable structure is possible owing to the turbulence that tremendously enhances the viscosity. Other famous example is the geodynamo. The turbulence, driven by the heat source, in the conducting fluid generates the structured magnetic field. In a system where turbulence generates structure, transitions take place.

These mutual regulations of structure and turbulence are ubiquitous for plasmas away from thermodynamical equilibrium, and is a main theme of the modern plasma physics. Within the theme of this International Toki Conference, a key issue is the fact that

(4) the electric field has a profound impact on the structural generation.

One of the most familiar example that the radial electric field plays an essential role in sustaining the structure is a bubble of soaped water. (Fig. 3). The radial electric field is generated near the surface. The electric field directs inward on the outer surface, and outward on the inner surface. These two layers of radial

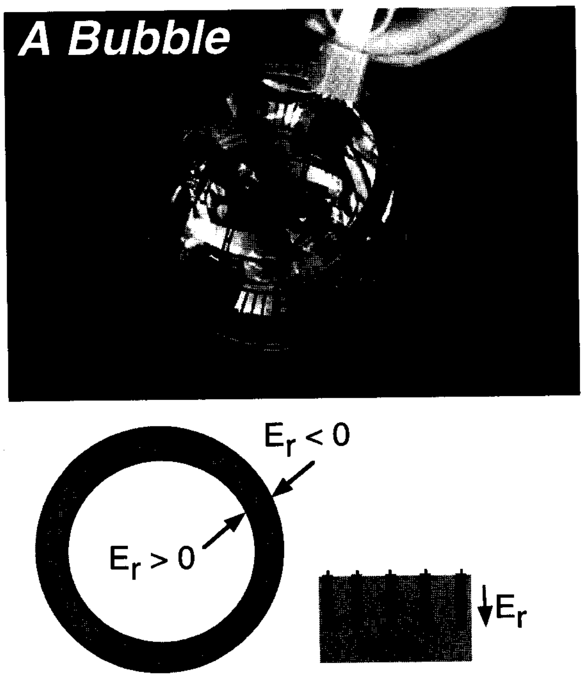

Fig. 3 Radial electric field in a bubble. Bubble (a) and schematic drawing of the radial electric field (b). Polymers are aligned normal to the surface. One end of the polymer is positively ionized: this end is much more solvable to oils, not to water. The other end the polymer is negatively charged: this end is akin to water. Electric field normal to the surface is generated near the surface.

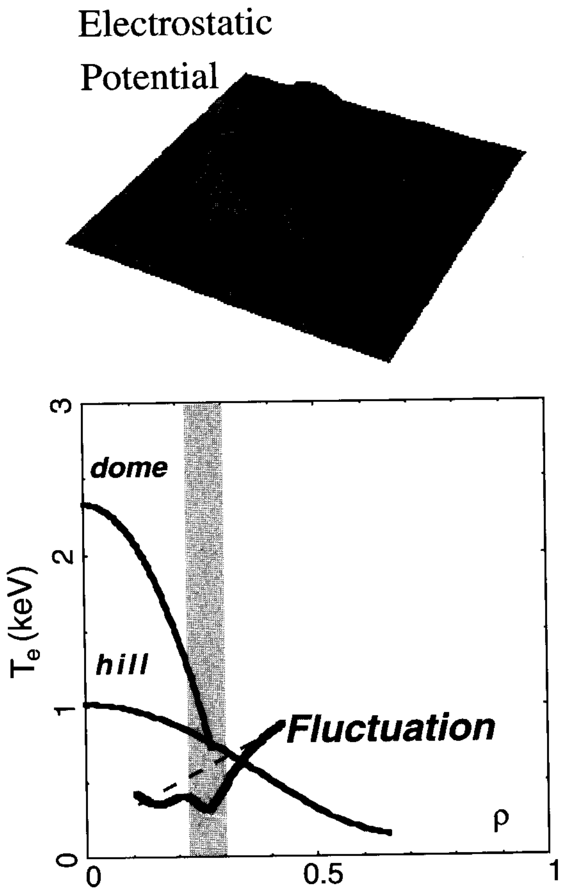

Fig. 4 Potential structure, plasma temperature and fluctuations. (Quoted from [3].)

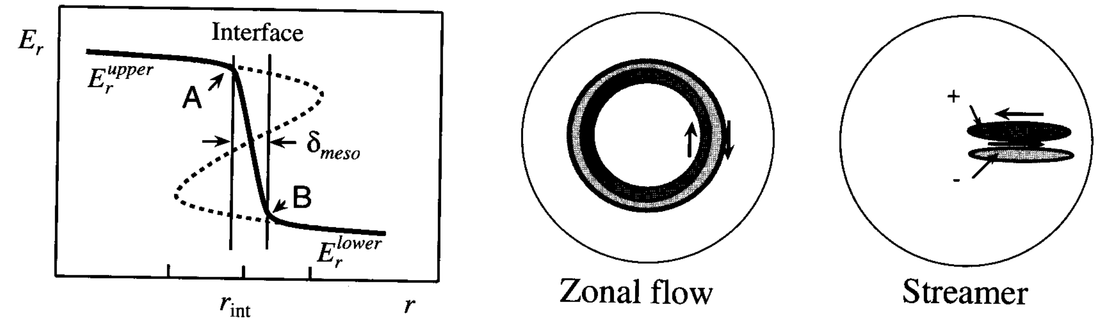

Fig. 5 Radial structure of the electric field domain interface (a). Zonal flow (b) and streamer (c) are illustrated on the poloidal cross-section.

electric field are repulsive. As a result of this repulsive interaction, a local deformation which changes the thickness of the bubble is restored. The bubble is stable against the perturbation that leads an irregularity in thickness. Owing to this stability, a bubble can survive very long time (until water molecules are lost by, e.g., evaporation).

A stability owing to the radial electric field structure has also been studied very intensively in magnetized plasmas. Role of the radial electric field in the improved confinement phenomena in fusion research is discussed later (§8). The importance of the meso-scale structure of the electrostatic potential is recognized more strongly. Examples of such structures are quoted from CHS experiments. (Fig. 4). A particular structure of the radial electric field is now known essential in determining the level of turbulence and transport.

There has been a substantial progress in understanding of the turbulence and turbulent transport. In a dimensional argument of turbulent transport, the turbulent transport coefficient is estimated by a relation

$$D = \gamma\ell^2$$

where γ is the decorrelation rate and ℓ is a decorrelation length of fluctuating motion of plasma elements. When the turbulence is induced by instabilities, a conventional picture is to estimate γ and ℓ by the growth rate γ_L and wave length $k_\perp^{-1}$ of the *linear* instability mode, obtaining $D = \gamma_L k_\perp^{-2}$. This turns out to be over simplified [4]. In a strong turbulent state, the decorrelation time and length are strongly influenced by the mesoscale structures (in particular that of the electric field). Typical examples of the mesoscale structures are the electric field domain interface, zonal flow and streamer. (Fig. 5). Nonlinear interactions cause complicated relations; the turbulent modes can generate or destroy mesoscale structure, and

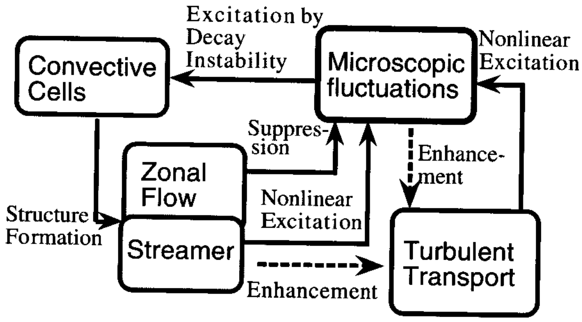

Fig. 6 Mutual regulations of microscopic fluctuations and mesoscale structures.

the domain interface and zonal flow suppress the turbulence while the streamer can further excite instabilities. (Fig. 6). Detailed explanations are given in reviews, e.g., [4]. Through these nonlinear links, a turbulent state self-regulates. Fluctuations are in many cases driven by *nonlinear instability* mechanisms, not by linear instability mechanisms. Turbulent state is often realized through the subcritical excitation. Thus turbulent states evolve accompanying transitions. The transitions are characterized by the autocorrelation time of fluctuations and mesoscale dynamics. Therefore it can take place in a much shorter time in comparison with the gradual evolution of global plasma parameters. This is a key in understanding the fact that abrupt changes of state (symmetry, noise level, transport coefficients, etc.) have been commonly observed in the laboratory plasmas as well as in space and astro plasmas. This understanding forms a basis for future investigations of turbulent phenomena in general.

4. Statistical Physics

If the equipartition law holds, the property of plasmas, in principle, could be derived by explicitly calculating collective modes or particle interactions. However, it is satisfied only in a limited case, and majority of plasmas are away from thermodynamical equilibrium. Example in §3 belongs to typical cases: turbulent states do not satisfy the equipartition law. For a set of quasi-two-dimensional fluctuations, the equipartition law predicts $\mathcal{E}_k \propto (k_B T) k_\perp$, where $\mathcal{E}_k$ is the energy density of the mode. For turbulent fluctuations, different power laws, e.g., $\mathcal{E}_k \propto k_\perp^{-3}$, have been derived, and magnitude is extremely larger than $\mathcal{E}_k \propto (k_B T) k_\perp$ [4]. Deviation from simple statistical law has also been confirmed in experiments. Observed probability density function of local fluctuation-induced flux deviates from Gaussian distribution, and contribution from rare but large-amplitude pulses has considerable impacts. (More basically, inhomogeneous systems are not extensive: When there are two inhomogeneous systems of the same temperature, the internal energy of combined system (A+B) is not necessarily equal to the sum of those of A and B. The extensiveness is one of the basis of conventional statistical physics.) A framework of the statistical physics, which is beyond the present nonequilibrium statistical physics (Boltzmann-Fermi-Bose statistics, Kubo formula, Prigogine's principle for minimum entropy production rate, etc.) is necessary.

In some cases (e.g., non-neutral plasmas), plasmas remain in a thermodynamical equilibrium state. However, the extensiveness is not necessarily guaranteed. Therefore, even if plasmas are in thermodynamical equilibrium, the conventional statistical theory may not be sufficient. One formal way of the statistical theory is to extend the definition of the entropy. As an example, Tsallis statistics is well known [5]. In Tsallis statistics, an extended 'entropy' is no longer extensive quantity. So far, it is recognized that the Tsallis entropy seems to capture some essential elements of turbulence, and that the structure of the non-neutral plasma might be explained better by employing such new statistics.

In a far nonequilibrium plasmas, turbulent fluctuations are associated with a large degree of freedom, and a result for particular case (e.g., $\mathcal{E}_k \propto k_\perp^{-3}$ for drift wave range instabilities) must be generalized as a law of statistical theory. Efforts in this direction have also been elaborated. Method of renormalization allows to separate nonlinear interactions into coherent drag and nonlinear self-noise excitation [6]. Based on this, it came to a point that a working hypothesis is proposed: statistics of turbulent modes could be described by the renormalized dissipation function $\mathcal{S}(\mathcal{E})$. (Fig. 7 [7]) It is another generalization of Boltzmann's entropy, and recovers Prigogine's entropy production rate as a limiting form as well. A minimum principle is proposed by use of function $\mathcal{S}(\mathcal{E})$. Power law statistics in the probability density function and in transition probability are obtained. The power index is dependent on the inhomogeneity (i.e., the magnitude of non-equilibrium deviations): This dependence might be a new 'universality' in far-non-equilibrium systems.

5. Irreversibility, Chaos and Control

The statistical theory is based on understanding of the irreversibility. The above-mentioned extension of statistical theory provides an H-theorem, that the access to the steady-state turbulent solution occurs. This access is observed as irreversibility, and the origin of the irreversibility has been one of the key issues in the

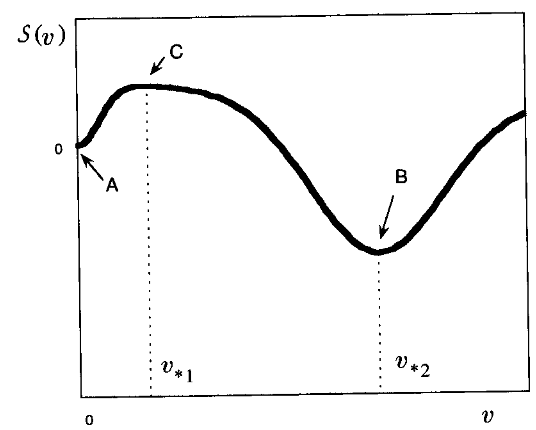

Fig. 7 Renormalized dissipation function as a function of the fluctuation level. (Schematic, quoted from [7].)

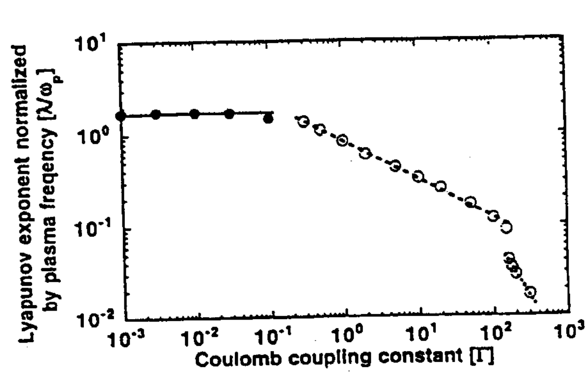

Fig. 8 Lyapunov exponents of electron motion in homogeneous plasmas. (Quoted from [8].)

physics. At the beginning of this century, the irreversibility is placed on the Boltzmann's Stosszahl Ansatz'. Now the origin is understood in terms of the Lyapunov exponent of the dynamical motions. The plasma theory has advanced to quantify the Lyapunov exponents in plasma interactions. (Example is shown in Fig. 8) The irreversibility in plasmas is becoming much clearer. In parallel with the understanding of the nature of chaos in plasma dynamics, the control of chaos is another important issue in plasma physics. A couple of reports have been made these days.

In physics (and more general sciences), understanding is achieved in efforts of trying to control the object. The irreversibility in thermodynamics, formulated as the second law of thermodynamics, has been investigated by employing the Gedanken-experiment of 'Maxwell's demon' (1870) [9]. It is now clear that the Maxwell's demon does not work. In observing the velocity of each particle by use of (say) light, Demon's temperature is increased. When the temperature becomes high, the Demon is subject to the random motion which is in proportion to temperature. Without being cooled, the Demon cannot continue to select proper particles.

Looking back the Maxwell's Demon, one sees a key issue in the control of chaos. The issue is a necessity of information and power in controlling a chaos. Others are, e.g., how one control the turbulence in which a large degree of freedoms with positive Lyapunov exponents, or whether the structure could be manipulated by the control of chaos. Understanding of the origin of irreversibility would be followed by the investigation to find a law behind various observations and present controlling experiments.

6. Symmetry

Investigation of the selection rule of the symmetry is another majour issue in modern physics. In a strong coupling plasmas, detailed study has been in progress. An example might be seen in a phase diagram of the hydrogen (the simplest atom). (Fig. 9) In a very high density region, the metal hydrogen is predicted, and the transition between plasma and liquid metal is studied. More variety of matter and states will be investigated in the future along this line of plasma physics. The selection rule of symmetry among gas, liquid, solid and crystal has been investigated.

For uch a research area, the solid state physics and condensed matter physics have been contributing together with plasma physics. In this direction, the plasma physics has advantages. The selection rule of symmetry and dynamics of strong coupling systems can also be studied by use of dust plasmas. One characteristic feature of dust plasma is that the larger charges of particles make the scale length longer. (Ikezi [11]). From this reason, the change of symmetry, such as 'melting' and change of crystal lattice, is observed in laboratory with a characteristic scale length like mm. This should be compared with the scale length of solid state where inter-particle distance is of the order of 10–100Å. This means that the plasma physics has an innovative microscope (e.g., order 10^5) in investigating the dynamics of interactions that drive a symmetry in a scale much longer than the binary interactions. Related with this, the nonequilibrium character of the charge of dust will also be illuminated by the light of turbulence and structure formation. Formation and destruction of symmetric structure have also been discussed for charged polimers [12].

Other subject of the symmetry is found in the transport problem. In the classical statistical physics, the Curie's principle is established. That is, the flows of scalar quantities (say, particle number density or internal energy) do not interfere those of vector quantities (say, momentum or angular momentum). This principle is deduced from the consideration of the symmetry. In thermodynamical equilibrium, the momentum flux is not caused by the gradient of pressure. This kind of principle must be investigated in plasmas. It is of interest what law is established in a non-neutral plasmas which can be near the thermodynamical equilibrium. In magnetic confinement devices, turbulence often

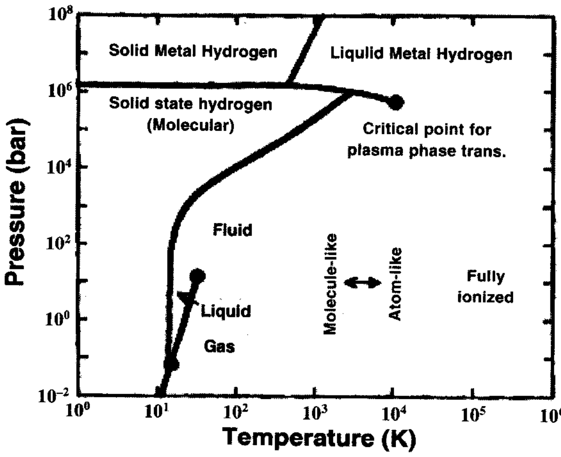

Fig. 9 Phase diagram of the hydrogen (Quoted from [10])

dominates the cross-field transport. In this case, the symmetry of the system is spontaneously violated by turbulence, and the Curie's principle does not hold. It has also been identified, that the momentum flow can be induced by the temperature gradient in tokamak experiments [13].

7. Momentum Transport

The law of momentum transport has profound impact on our understanding of the universe. In the gravitational system like our galaxy and universe, the gravitational energy is released as kinetic (or photonic) energy through the exchange of momentum and momentum transport. When the angular momentum of some element, which is captured by the gravitational central force, is conserved, the gravitational energy is not released. Once the exchange of angular momentum takes place between many elements in this gravitational system, some elements start to fall down so that the total kinetic energy is released. Understating of the evolution of astrophysical objects (accretion disks, active galactic nuclei, etc.) will be promoted by the progress of understanding of the transport of angular momentum through interaction of plasmas and electromagnetic fields. The dynamo physics is also an important element in this subject. (Fig. 10)

Change of angular momentum includes the generation of magnetic field through plasma dynamics. One of the most famous problems is the origin of geodynamo. In addition, the generation of the large scale magnetic field could have a strong influence to modify our view of the cosmology. It is now becoming clear that substantial part of the astrophysical energy is stored in a form of the magnetic energy [14]. While the

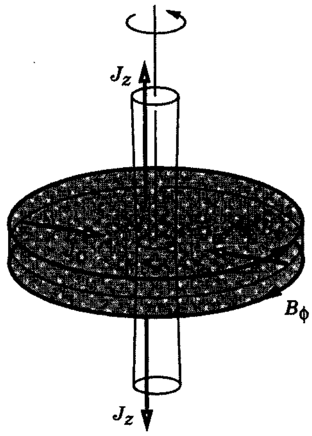

Fig.10 A model of accretion disk (quoted from [4]).

un-identified 'dark-matter' still occupies the majority of the speculated total mass of this cosmos, the role of the magnetic field energy should not be underestimated. One example might be considered in conjunction with the future of this cosmos. If the total energy of the universe is negative, the universe which is now expanding with the present Hubble constant will start to shrink again. In a final state the gravitational force causes the collapse. The rate of collapse should be influenced strongly by the presence of magnetic field. The magnetic energy resists against collapse if the magnetic flux is conserved. The rate of the flux annihilation, which is solely determined by the plasma dynamics, enters as a mechanism that dictates the time rate of evolution.

8. Improved Confinement

The issues of the turbulence transition, mesoscale dynamics, momentum transport and irreversibility, have also been investigated in the context of understanding of the improved confinement. In the area of magnetic confinement research of plasmas, the problem of the improved confinement played a strong driving force for the evolution of the plasma physics. After the finding of the H-mode by Wagner and collaborators on ASDEX tokamak in 1982 [15], we had now two decades of research.

The finding of the H-mode has opened a new world for plasma confinement research, and many improved confinement modes have been found later. Some examples are listed as follows: CNTR-NBI mode, Core H-mode, ERS-mode, Helical system ITB, High-β_p H-mode, High-β_p mode, High-ℓ_i mode, High T_i H-mode, High T_i mode, HIT mode, IL-mode, I-mode, IOC, LH-mode, Pellet mode, PEP H-mode, RIM, Supershot, VH-mode, Z-mode (Alphabetical order: It is not exhaustive.)

Improved confinement modes had profound impact on fusion research. For instance, the design study of the fusion experimental reactor has shown that the cost of the device follows an empirical fitting

$$C \propto H^{-1.3}$$

where C is a cost and H is an enhancement factor of the energy confinement time over the L-mode scaling [16]. The finding of the H-mode made the fusion experimental reactor realistic.

In addition to this impact on fusion research, the H-mode and following series of improved confinement modes have propelled the plasma physics of high temperature plasmas. Many elements of progress beyond the quasi-linear theory of turbulence, have been explored being motivated by the H-mode phenomena. As is discussed in §3, the role of the radial electric field structure has been understood in the efforts to study the mechanism of the H-mode. Subsequently, the mutual regulating features of turbulence and potential structures have attracted interests of plasma physicist. Present working hypotheses, being initiated by S-I Itoh, Shaing, Diamond, and coworkers, is the transition of turbulence coupled by the mesoscale electric structure. This is widely accepted, and a lot of efforts are done in this direction. (For a theoretical review, see, e.g., [4,17] and for experimental ones, see, e.g., [18].) It must be stressed, however, a direct confirmation of the causality has not yet been established. The time and spatial scale of transition is not yet been fully understood. Further breakthrough is still looked for. Similarly, there are many un-explained peculiar phenomena in toroidal confinement: the origin of particle pinch, the transient response of profile against change of external conditions, the sudden occurrence of collapses, etc. Understanding of these phenomena, if obtained, will give an insight into the general mechanism of structural formation in the universe.

9. Synergy of Methodology

In search of the breakthrough of the physics of the structural formation in plasmas and the role of the potential, one must also be keen about the methodology of the study. It should be emphasized that the synergy of physics methods must be intentionally pursued. As the physics methods, we have experimental, theoretical and computational methods. These three dimensions of methods are complementary each other. Uniting research of these methods, one could think of the future progress.

Let us take here one example: Divertor bias and bifurcation of electric field. *Experiments* on TEXTOR has identified that the radial electric field near plasma surface is subject to bifurcation. If the applied voltage exceeds a threshold value, there appear a solitary radial electric field. This phenomenon is explained by *theory*. By considering the nonlinearlity in the relation between the radial current and radial electric field, $J_r[E_r]$, the solitary electric field is shown to exist. Finally, the nonlinear simulation has shown that the bifurcation to the solitary radial electric field can occur. (Fig. 11) The experiments provide the finding of events and control. Theory gives modelling and understanding of the mechanism, so that a scaling property is clarified.

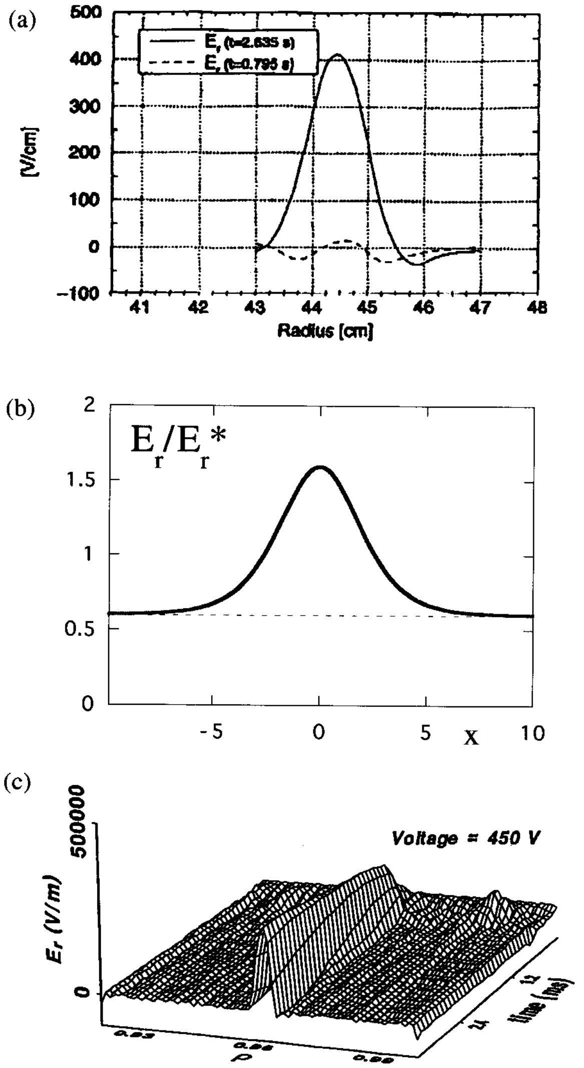

Fig.11 Bifurcation to solitary radial electric field near plasma edge induced by the biased limiter. Experimental result [19], theory [20] and Monte Carlo simulation [21].

Numerical simulation can treat a full expression of nonlinear interactions, and yields quantitative result. Understanding of the potential and structure formation could be advanced by the synergy of the research methods.

10. Exploring Future Plasma Physics

In this article, a perspective is discussed for the future of the plasma physics in the area of the theme of this International Toki Conference. After reviewing the future direction of research, one comes back to a question *Why we are proud of plasma physics?* The reason is that the plasma physics is a high-quality and challenging area of science. In concluding so, it is necessary to identify how to judge the quality of scientific research. Someone might judge by wide applicability, influences on daily life and industry, and so one. In addition, it might be worth stressing the following aspects in the judge:

1. Impact on human recognition of nature
2. Answer to long-lasting fundamental problem
3. Beauty in a law

A typical example of the long-lasting fundamental problem is shown in Figure 12. The law of all things that flow has remained a fundamental question, and the plasma physics will give important contribution to the solution of this historical enigma. Plasma physics/ science satisfies these three criteria in the 21st century, and will be recognized as one high-quality science. Such progress should make us much more proud of the research of plasma physics.

Acknowledgements

Discussions with participants of the 11th International Toki Conference are acknowledged. In addition, the author would like to acknowledge discussion and collaboration with Drs. S.-I. Itoh, A. Fukuyama, M. Yagi, A. Yoshizawa, K. Ida, Y. Miura, A. Fujisawa, M. Azumi, K. Makishima, K. Nishikawa, T. Ohkawa, S. Yoshikawa, R. Balescu, J.W. Connor, P. H. Diamond, B.B. Kadomtsev, T. Klinger, J. Krommes, K. Lackner, U. Stroth, F. Wagner, R.R. Weynants.

Παντα ρει
All things flow and nothing lasts (Heraclitus)

子在川上曰逝者如斯夫不舍晝夜（孔子）
逝くものは斯くの如きか昼夜をおかず

Fig. 12 Historical problem for human recognition of dynamics of the universe.

References

[1] For instance, *International Conference on Plasma Physics* 1996 (Nagoya), 1998 (Prague), 2000 (Quebec).

[2] R. Kimura, *Science of Flows* (Tokai Univ. Press, 2nd ed., 1985) [*in Japanese*].

[3] A. Fujisawa, *et al.*, Phys. Plasmas **7**, 4152 (2000).

[4] A. Yoshizawa, S.-I. Itoh, K. Itoh, N. Yokoi, Plasma Phys. Control. Fusion **43**, R1 (2001).

[5] C. Zallis, J. Stat. Phys. **52** ,479 (1988).

[6] J. A. Krommes, Phys. Rev. E **53**, 4865 (1996).

[7] S.-I. Itoh and K. Itoh, J. Phys. Soc. Jpn. **69**, 408 (2000).

[8] Y. Ueshima, K. Nishihara, D.M. Barnett, T. Tajima, H. Furukawa, Phys. Rev. Lett. **79**, 2249 (1997) .

[9] M. Toda, *Looking through entropy* (Iwanami, 1987) [In Japanese].

[10] H. Totsuji, J. Plasma Fusion Res. **76**, 331 (2000).

[11] H. Ikezi, Phys. Fluids **29**, 1764 (1986).

[12] M. Tanaka and T. Tanaka, Phys. Rev. E **62**, 3803 (2000).

[13] K. Ida, Y. Miura, T. Matsuda, K. Itoh, S. Hidekuma, S.-I. Itoh and JFT-2M Group, Phys. Rev. Lett. **74**, 1990 (1995).

[14] K. Makishima, Plasma Phys. Control. Fusion **39**, 15 (1997).

[15] F. Wagner, *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).

[16] K. Itoh, S.-I. Itoh, A. Fukuyama, Fusion Engineering and Design **15**, 297 (1992).

[17] K. Itoh, S.-I. Itoh, A Fukuyama, *Transport and Structural Formation in Plasmas* (IOP, England, 1999).

[18] K. Ida, Plasma Phys. Control. Fusion **40**, 1429 (1998).

[19] For experimental set-up, see R. R. Weynants, S. Jachmich, G. Van Oost, Plasma Phys. Control. Fusion **40**, 635 (1998).

[20] K. Itoh, S.-I. Itoh, M. Yagi, A. Fukuyama, Phys. Plasmas **5**, 4121 (1998).

[21] J.A. Heikkinen, T.P. Kiviniemi, A.G. Peeters, Phys. Rev. Lett. **84**, 487 (2000).