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Frontier Physics of Extremely non-Equilibrium Plasmas
極限プラズマ物理学の最前線

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The expanding frontiers of extreme state plasmas are briefly overviewed. One thread of thoughts that unifies the progresses, which have been achieved in subdivided communities on specific parameters and configurations of plasmas, is explained. Synthetic researches on extreme state plasmas far from equilibrium are introduced, and the research on turbulence, fields and structure formation is illustrated. The futurology is discussed from this point of view.

1. Problem definition

The empirical knowledge of mankind about plasmas has dramatically expanded and now covers those with extreme parameters, e.g., the
*high temperature plasmas in magnetic confinement devices (several tens of keV),
* high density plasmas in laser-produced plasmas (thousand times of solid density),
* strong turbulence in basic as well as fusion plasma experimental devices,
* intense charge beam (~10^8A in 5μ ϕ),
* extremely fine resolution of plasma structure in plasma processing,
* approach to precise dynamics in solar plasmas,
* emission of photons by plasmas in early universe,
* high energy density quark-gluon plasmas,
* plasma interacting with genes, cells and organs,
etc. (See ref.[1]-[5] for introduction to varieties of extreme state plasmas.) Efforts to unify understanding from empirical progresses that have been achieved for specific plasmas (e.g., magnetic fusion, inertial fusion, plasma processing, space-astro plasmas, bio plasmas, etc.) have been pursued. For example, the 'Research network on non-equilibrium and extreme state plasmas' project [6] has been launched, in order to accelerate the leading edge of plasma physics in the arena of modern science. (It is selected in 'Japanese Master Plan of Large Research Projects' by Science Council of Japan [7].) Key physics area of extreme state plasmas is the deviation from thermal equilibrium, evolution of turbulence, and dynamical structure formation, which are illuminated here.

2. Physics picture of plasma turbulence

Importance of turbulence in understanding and applying plasmas has been recognized for more than five decades of plasma research. The most stimulating advancements are the change of view from 'linear, local and deterministic' picture to '*nonlinear, nonlocal and probabilistic*' picture. The nonlinear mechanisms are essential not only in the suppression processes, but also in the *generation* processes of turbulence. (E.g., subcritical excitation of instabilities and nonlinear drive of meso and macroscopic fluctuations by micro turbulence have been understood in detail.)

3. Advanced understanding

The quantitative measurements of nonlinear processes in plasma turbulence have been realized and made advancement of scientific knowledge, as is explained in this talk.

The generation of meso and macroscopic flows by microscopic turbulence is an essential process that governs the structure formation in nature. Turbulences mix inhomogeneous matters, so as to '*homogenize*' the media. At the same time, turbulence generates the meso and macroscopic axial vector fields (such as zonal flow, zonal magnetic fields, mean electric-field/flow, and mean magnetic field), which induce the steep spatial gradient of turbulence fields, thus tends to sharpen the edge (interface) of inhomogeneous plasmas, which shows a clear outline of global structure. The discovery of zonal magnetic fields is the first experimental evidence that the micro thermal convection generates the large-scale magnetic structure, which has long been accepted as 'dynamo hypothesis'. These two actions, i.e., homogenization and sustainment of interface, govern the generation and decay of 'structures' in plasmas. This partly answers the historical enigma of the law of '*panta rhei*'.

The clarification of origin of anomalous transport in fusion devices, has also strong impact.

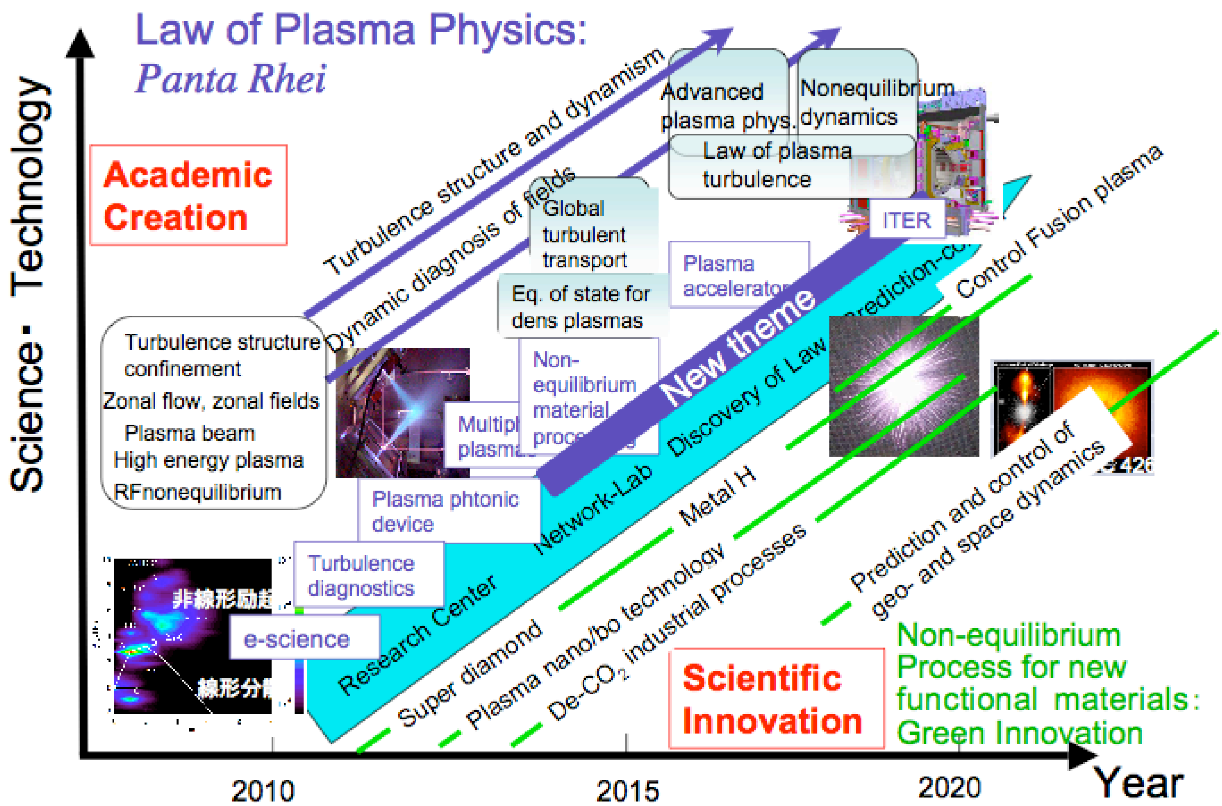

Fig.1: Near future breakthrough and innovations, which are driven by plasma physics [6].

The understanding of H-mode and the experimental identification of zonal flow have decisive roles in the future perspective of the burning plasmas in ITER.

Following illustrative examples are described:
* The progress in the statistical theory of plasma turbulence, in which the important role of 'incoherent' part by nonlinear interaction has been highlighted [8] (the phase space granulation, stochastic forces, and probabilistic transitions etc.);
* The first-principle-based experiments, in which the quantitative verification of theoretical modelling has been performed.

3. Summary

Researchers on plasmas have realized various kinds of extreme state plasmas, which will provide arena for the development of future physics and science in general. Progresses, which have been achieved in subdivided communities on specific parameters and configurations of plasmas, can be accelerated by a unified principle of plasma physics. As an example, the synthetic research project on extreme state plasmas far from equilibrium is introduced, and the research on turbulence, fields and structure formation is illustrated. The futurology is discussed based on the planning of this project (See the figure 1).

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