Summary of the 19th International Toki Conference - Advanced Physics in Plasma and Fusion Research

Kimitaka ITOH

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

(Received 20 March 2010 / Accepted 20 April 2010)

This article summarizes advanced physics in plasma and fusion research, which was covered by the 19th International Toki Conference (ITC). Summary is made from the viewpoint of progress of physics of nonequilibrium properties of plasmas, putting an emphasis upon the theme '*Knowledge* must be developed into *understanding*'. The aspects of advanced physics in this ITC was assessed in the issues: (i) advance in knowledge of confinement, (ii) multi-scale turbulent structure formation, (iii) transport processes, continued (nonlocal transport, statistical theory), (iv) advanced diagnostics, (v) reconnection, magnetic islands and MHD activities, (vi) plasma atomic molecular physics, (vii) integrated modelling, (viii) problem definitions for reactor studies, (ix) solar, space and astrophysical plasmas, (x) nano-bio plasmas, and (xi) further extensions. This report summarizes achievements in plasma physics with the perspective of 20 years of National Institute of Fusion Science after its inauguration.

Keywords: advanced physics in plasma and fusion research, nonequilibrium properties of plasmas, confinement, multi-scale turbulent structure formation, nonlocal transport, statistical theory, advanced diagnostics, reconnection, islands and MHD activities, plasma atomic molecular physics, integrated modelling, problem definitions for reactor studies, solar, space and astrophysical plasmas, nano-bio plasmas, 20 years of NIFS

DOI: 10.1585/pfr.5.S2118

1. Introduction

The 19th International Toki Conference was held on the subject of advanced physics in plasma and fusion research. The theme is very wide but the conference was designed to present synthetic view on the progress of this research field, with the perspective of 20 years of National Institute of Fusion Science (NIFS) after its inauguration. This ITC is an arena where the state-of-art plasma physics is surveyed by international researchers.

Where are we now, after the two decades of NIFS? Figure 1 illustrates the evolution of experimental devices in magnetic confinement fusion research. In the beginning, circular tokamaks have evolved; then non-circular tokamaks followed, realizing the possibility of burning plasma experiment, ITER. The stellarators/helical systems have shown a delay in growth, in the early phase. The establishment of NIFS has lead LHD. This device was envisioned in early 80's that, in the age of operation of LHD, the issue to realize stationary sustenance of confined plasma should be the key problem in world fusion research. The fourth new wave is the evolution of spherical tokamaks, which may allow very high β plasmas. One should also stress that small-scale basic experimental devices have renaissance in the last decade, in order to study, quantitatively, fundamental nonlinear processes in confined plasmas. There are a lot of lessons after the five decades. First of all, the *discoveries* have driven progress of physics. A fundamental knowledge is that the size and shape of plasma influence the quality of confinement (such as 'diffusivity'). From the physics viewpoint, people have searched for the law of plasma system far from thermal equilibrium. For the realization of controlled fusion, one has been keen about how this knowledge can be applied to accelerate the realization of fusion energy.

Associated with the varieties of motivations of re-

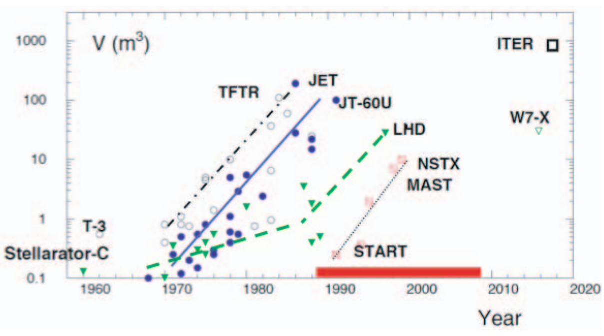

Fig. 1 Evolution of experimental devices in magnetic confinement fusion research and two decades of NIFS. (Symbols: Open circular and closed circular indicate circular tokamaks and shaped tokamaks, respectively. Triangle is for helical systems and open rectangular is for spherical tokamaks.)

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

search (Fig. 2), the range of scales of plasmas, which were reported in ITC-19, is very wide (Table 1). The range in the spatial scale is more than 10^{14} and that in time scale is more than 10^{21}. The question of 'how far are we away from universal physics law?' has a touchstone in this ITC-19, i.e., 'to what extent of the range, a particular way of thinking can explain observations?' we away from universal physics law?' has a touchstone in this ITC-19, i.e., 'to what extent of the range, a particular way of thinking can explain observations?'

This report summarizes the ITC-19 from the viewpoint of progress of physics of nonequilibrium properties of plasmas, putting an emphasis upon the theme '*Knowledge* must be developed into *understanding*'. The aspects of advanced physics in this ITC may be assessed in the issues: (i) Advance in knowledge of confinement, (ii) Multi-scale turbulent structure formation, (iii) Transport processes, continued (nonlocal transport, statistical theory, Alfven eigenmodes, etc.), (iv) Advanced diagnostics, (v) Reconnection, magnetic islands, and MHD activities, (vi) Plasma atomic molecular physics, (vii) Integrated modelling, (viii) Problem definitions for reactor studies, (ix) Solar, space and astrophysical plasmas, (x) Nano-bio plasmas, and (xi) further extensions. This summary is planned to provide a global description of the conference achievement. We leave explanations of individual presentations to the literature [1], and limit the references to introductory purposes.

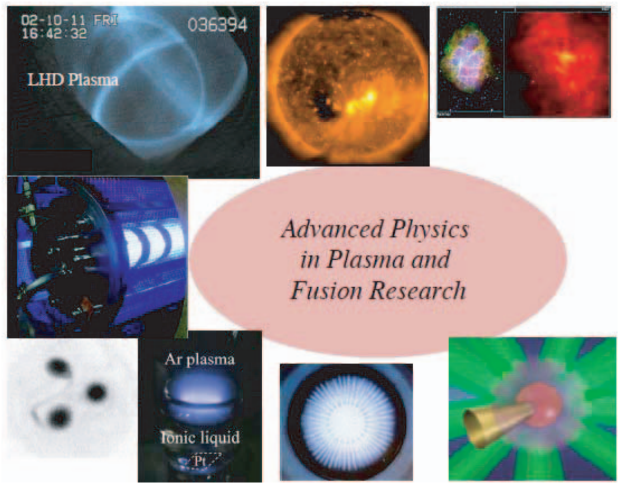

Fig. 2 Varieties of motivations of researches, which are reported in ITC-19.

Table 1 Range of scales reported in ITC-19.

Plasma	Length (m)	Time (sec)
Sun	> 10^{9}	> 10^{10}
MCF, e.g., LHD	1	1
Basic Exp	10^{-1}	10^{-2}
ICF	10^{-5}	10^{-10} – 10^{-11}
Nano-bio plasma	10^{-1} - 10^{-5}	1 - 10^{-5}
Range	> 10^{14}	> 10^{21}

2. Advance in Knowledge of Confinement

Noticing the change of physical quantity that is subject to the analysis highlights the progress in confinement research. In the beginning of confinement research, the energy confinement time τ_E, one scalar coefficient, was the central parameter. As a progress in spatial resolution of observations, the gradient-flux relation has been measured. After the discoveries of various improved confinement modes, the *nonlinear* relation in gradient-flux relation is now widely recognized [2]. Recent progress in physics can be seen in the improvement in the precise measurement of temporal evolution. The study of dynamics has induced a new knowledge. The fast transmission of *change of transport property* occurs much faster than the diffusive propagation of change. The problem of fast transmission has been observed from early stage of fusion research, such as heat pulse propagation after sawtooth, response to the ELMs, impact of pellet, and so on [3]. The transport process is (at least partly but could be substantially) caused by *nonlocal* mechanisms [4]. The precise experimental measurement on LHD has unambiguously demonstrated the *nonlinear and nonlocal* nature of transport processes in transport [5] (Fig. 3). This is the direction, in which the future research should achieve progresses. In addition to assessment of generality in confine-

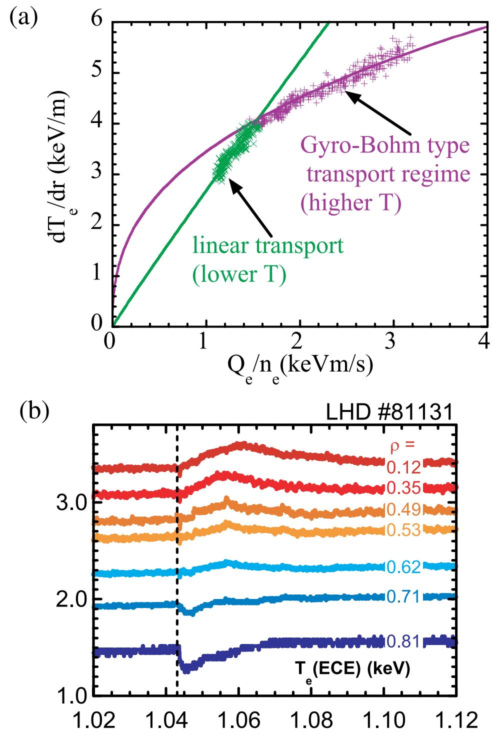

Fig. 3 Nonlinear and nonlocal nature of transport processes (LHD observation [5]).

ment, new discoveries of new plasma states have continued. The discovery of the impurity hole has followed that of the internal diffusion barrier plasma.

Progresses in understanding, which is driven by advance in knowledge of plasma confinement, are discussed in subsequent chapters.

3. Multi-scale Turbulent Structure Formation and Transport

Physics picture for the plasma turbulence and turbulent transport has made distinctive improvements in the last decades. First, not only microscopic fluctuations, but also nonlinearly-driven mesoscale fluctuations are known to control cooperatively turbulent transport [6]. Second, quantitative studies can be explicitly realized by synthesizing theory, simulation and experiment [7]. In the assessment of these advancements in physics of turbulent structure formation, two parameters are chosen. One is the relative amplitude of fluctuations, say, $e\tilde{\phi}/T$, and the number of degree of freedom of relevant fluctuations. The former is a parameter that quantifies the magnitude of nonlinear interaction among three interacting waves. The latter is the key in causing variety in structures, such as meso-scale and large-scale flow, spreading and avalanche, condensation of fluctuations in the localized isolated structures, and others. By use of this diagram, studies on small basic experimental devices and those on large devices are unified (Fig. 4).

A unifying picture is that drift wave turbulence coexists mesoscale flows via disparate-scale interactions. In the plenary talk, Diamond has surveyed the issue, and presented the momentum theorem, which unifies plasma turbulence and geostrophic turbulence. This way of understanding applies all the range of plasmas that are explained in this ITC.

Being lead by the theoretical insight and simulational predictions, experimental verifications on drift wave – zonal flow system have been enriched [8]. Observations of low frequency zonal flow and geodesic acoustic mode (GAM) became routine in toroidal plasmas, and were reported in ITC-19 (ASDEX-U, HL-2A, HT-7, LHD). Scaling of GAM frequency and plasma parameters is established. Fluctuation suppression by zonal flows was widely observed. Flow driven by fluctuations was reported in detail (CDX, LMD-U). The turbulent transport that is driven by microscopic drift waves is controlled strongly by the energy partition between fluctuations and flows. Thus the transport coefficient is substantially influenced by the damping rate of mesoscale flows. Not only mean radial electric field but also mesoscale counterparts control the turbulent transport.

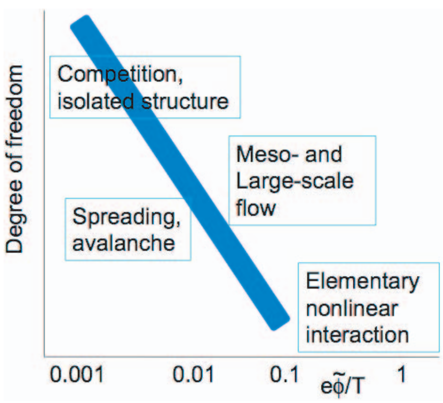

Fig. 4 Characterization of turbulence and turbulent structure.

Nonlinear interactions among excited fluctuations are studied in detail (LMD-U). Drift wave anatomy is available now. Competition among modes is studied, and transition between different turbulent states is observed. In the anatomy, bispectral analysis is routinely applied. It should be stressed that these measurement have given quantitative evaluation on the nonlinear interactions (CDX, LMD-U, QT-U). Other nonlinear structure is the blobs, for which reports are made on various devices (TORPEX, QUEST, FT-2, LHD).

The electron plasmas provide an arena where detailed observation of nonlinear cascade is observed. In a plenary talk, dynamics in structure, cascade of turbulence, and conservation property at the collapse were described in detail. The cascade in the enstrophy spectra and the inverse cascade in the energy spectra were observed in pure electron plasmas. At the onset of collapse, it was reported that the total energy is nearly conserved, while the total enstrophy is reduced suddenly. The evolution of the pure electron plasma is not a dual cascade where two invariants (total energy and total enstrophy) exist. Instead, selective decay of enstrophy occurs (under conserved energy), *a la* Taylor relaxation problem in MHD turbulence.

On the issue of nonlinear interaction of drift waves, many reports were made on theory and simulation. General momentum theorem, $E \times B$ frame shearing, driven flow, solitary dipole electric field, collisions and entropy balance, GAMs in LHD, ion-temperature gradient (ITG) modes and ZFs, viscosity and transport in three-dimensional braided magnetic fields, vortex formation in ETG turbulence, etc. An assessment on turbulence by micro fluctuation is commented here. (i) In the evaluation of turbulent transport, $\chi = \gamma_N k_N^{-2}$, the nonlinear decorrelations (γ_N, k_N) are essential and cannot be replaced by quasilinear estimate. (ii) When multiple instabilities coexist, the naïve argument, $\chi = \gamma_A k_A^{-2} + \gamma_B k_B^{-2} + \ldots..$, is invalid. (iii) The ratio of two different fluxes can close to the ratio of corresponding quasilinear fluxes for some circumstances. However, this does not hold for the case of radial flux of poloidal momentum.

It should be remarked that two directions of progress in the numerical simulation collaborated: the numerical method, and the analysis method for simulation data.

This area of the research is a prototypical example in which uniting theory, simulation and experiment has given firm basis for the advanced physics. This advance provides a new clue for the control of turbulent transport via controlling geometry, for instance, the reduction of geodesic curvature.

4. Transport Processes, Continued

Interaction of microscopic fluctuations with the mesoscale structures naturally introduces the nonlocal property in the turbulent transport. Two prototypical processes are illustrated in Fig. 5. One process is the interaction of microscopic fluctuations which are separated by the long distance (Fig. 5a). When the radial separation is much longer than the correlation length of micro fluctuations, two groups of micro fluctuations do not have interactions directly, but through change of global plasma parameter (i.e., slow diffusive process). However, when mesoscale fluctuations (the correlation length of which is much longer than those of micro fluctuations) coexist, radially-separated micro fluctuations interact each other via mesoscale (or long-rage) fluctuations [4]. This leads to the *integral formulation* for the gradient-flux relation. Zaslavsky has considered more general cases and has proposed fractional kinetics [9]. The other process is the avalanche and turbulence spreading (Fig. 5b). The clump of fluctuations can propagate in radius, so that the perturbed density (temperature) can propagate in radius [10]. The propagation of fluctuation clumps (avalanche) is not necessarily outward, so that the turbulence spreading can play a role in the barrier formation. Such advancement in the physics of nonlocal transport was discussed from theory, transport modeling and direct nonlinear simulations.

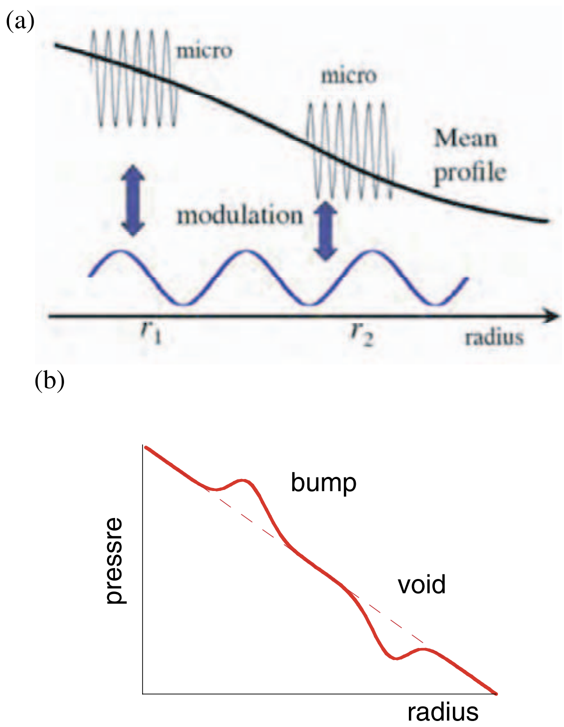

Fig. 5 Two prototypical mechanisms that cause nonlocal nature in turbulent transport.

Related to the progress of multiple scale turbulence, statistical theory of turbulence has advanced too. In the formulation of course-grained equations from original equations with larger-degree-of-freedoms, the drag and noise must be kept in equal-footing manner. For this purpose, methodological application of statistical approach is necessary. Dynamical friction by granulations was reported, and excitation of islands by fluctuating force was discussed.

The energetic particles play a role in the nonlocal nature of transport. Alfven eigenmodes can be driven by (radially-inhomogeneous) energetic particles. Alfven eigenmodes have long radial wavelength so that the successive transportation of hot particles from core to edge takes place. Review is made in this ITC. An elementary process in electron scattering was discussed, and nonlinear simulation was reported. In experiments, Alfven eigenmodes have been routinely observed in large and medium size devices. Identification of Alfven eigenmodes on LHD device was reported, and coexistence with GAMs was reported as well.

5. Advanced Diagnostics

Surveying the progress in understanding of turbulence and turbulent transport, one is impressed by the fact that such advance has become possible by the development of the diagnostics. In this ITC, a lot of dramatic progress in observation was reported, e.g., detailed observation of Sun by Hinode [11]. The observation illuminates the physics of solar dynamics in detail, and impresses the advancement of diagnostics. Now, we ask ourselves 'what is called advanced diagnostic?'. One may formulate advanced diagnostic such as: (i) it describes multidimensional, multiple-scale fluctuations, (ii) it quantifies causal relations in observed processes, and (iii) it empowers human ability of induction. Satisfying this criterion, large number of reports was presented in this ITC.

Flourishing is the 2D imaging. The ECE imaging (LHD, KSTAR, Gamma-10, etc.), microwave imaging reflectometry, high-speed camera, imaging bolometer, and phase contrast imaging. The discovery of the localized energy ejection at the onset of sawtooth crash [12] was one of the best examples for this advanced diagnostics. By this finding, a couple of working hypotheses were rejected clearly (no working hypothesis was found fully satisfactory), and touchstone for the future and correct modelling was placed.

Multi-channel diagnostics is approaching routine. Multi-channel microwave diagnostics are also advanced; reflectometer, Doppler reflectometry. Multi-channel Bremsstrahlung, and Multi-wave-length range spectrometer were also reported. The heavy ion beam probe (HIBP) is essential in measuring the electric field in plasmas, and has shown successes. Langmuir probes are considered to be classic and elementary, but have revived recently for the purpose of the detailed analysis.

Looking into the freedom in the velocity space, we heard about the Ion-cyclotron emission, high-energy particle diagnostics, and distribution function itself. Thomson scattering is routine for electron temperature and was extended to collective Thomson scattering for ion distribution function. Progresses on laser induced fluorescence (HYPER-I) and on electron spectrometer were also reported (Gekko-XII).

In addition to these progresses in methods to obtain multi-channel data, noticeable progress has been made in the percept of data, i.e., in reconstruction of data and in analyzing the data. Visualization is powerful for the plasma diagnosis. Techniques are reviewed, and highlights of examples include application of the virtual reality and visualization of magnetic field line in 3D configurations (WEGA). Theory-aided data interpretation is proving advantage in providing full description of the events, for which only part of features are given by real measurements. MHD equilibrium construction is the area where a lot of success was reported. Summarizing these movements, reports were made on 'turbulence diagnostic simulator', which is the method to integrate theory, simulation and measurement to provide physics understanding. Much more focus in this direction is looked for, in order to achieve a progress in the future experimental research.

6. Reconnection, Magnetic Islands and MHD Activities

Another fundamental process in nonequilibrium plasma physics is the issue of magnetic reconnection. Varieties of phenomena were reported in this ITC-19, some of prototypical examples are summarized in Fig. 6. In this figure, two parameters (magnetic Reynolds number and relative magnitude of perturbation of interest) are chosen, and phenomena are categorized accordingly.

The central issue is the fast change of the magnetic topology [13]. The reconnection that obeys the resistive

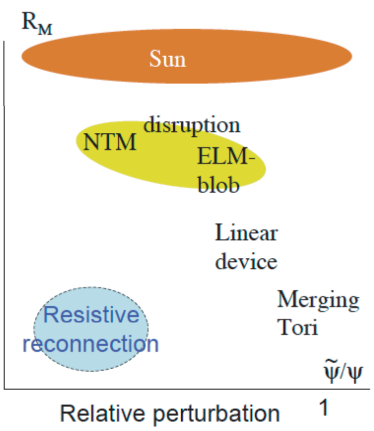

Fig. 6 Varieties of phenomena associated with magnetic reconnection.

time scale is found only in the regime of weak perturbation and at high resistivity. The central issues in dynamic phenomena are categorized in to two problem (i) origin of fast reconnection and (ii) problem of sudden onset.

Origins of fast reconnection were discussed by many authors. Examples include combination of lower hybrid drift instability and drift kink instability, role of three-dimensional topology near X-point (LAPD), and others. Advanced diagnostics (discussed in §5) are also powerful in clarifying the role of complex topology associated in the reconnection processes. More and more precise measurements are available of the evolution of magnetic islands, and the role of magnetic islands in toroidal plasmas is becoming quantified.

Trigger of MHD events is a key problem when plasma temperature becomes higher or plasmas are larger. Reasons of large magnetic deformation, reconnection, bursts, etc., have been explained in last decades; as the origins to drive deformation have become clearer, the mysteries, i.e., why such deformations are prohibited before the onset of deformation, have become apparent. This 'trigger problem' was discussed in this ITC.

Dynamics of tori was reported in detail; compact tori (spheromak, field reversal configuration), reverse field pinch, and so on. In the process of merging, the induction of rotation by the expense of flux change was reported, and merits further studies. Edge localized modes (ELMs) are attracting attentions. The understanding of this phenomenon is attractive in academic challenge, and the control of ELMs is demanding in the design of fusion devices. Conceptual model of magnetic topology change was reported. ELMs control by use of resonant magnetic perturbations has attracted attentions in the context of the design of ITER [14]. The test of resonant magnetic perturbation on JET was reported.

7. Plasma Atomic and Molecular Physics

Under the heading of 'plasma atomic and molecular (PAM) physics', issues of 'plasma and light' and 'plasma and solid' are also assessed here.

The interaction of plasma and light is one of central issues in nonequilibrium plasma physics. Basic laws of emission from a few atoms are well known. Thus, the nonequilibrium property in the plasma is the essence in this problem [15]. The challenge is to establish the relation between 'knowledge of light' and 'knowledge of plasmas'. This issue is essential, because the knowledge of plasma is often transferred to us via light propagation. This is the case of astrophysical objects and of high temperature laboratory plasmas, for which direct contact to the interior is prohibited. In the line of nonequilibrium interaction between plasmas and light, enthusiastic work has been reported here on inertial confinement fusion research, on the warm dense matter, on magnetic confinement plasmas, on photo ionization of astrophysical objects, on lithography, etc. One recognizes the plasmas in this list cover all of the range in Table 1.

The study of interaction between plasma, atom and molecule was discussed by many authors, and substantial progress was reported. Elementary processes in PAM physics, charge exchange process and electron captures, were described in detail. Measurement has advanced so that internal degree of freedom of atoms was measured on confinement devices. For instance, the densities of hydrogen atoms at $n = 1$ and $n = 2$ levels, respectively, were quantified on LHD. Neutral density, which plays a key role in plasma dynamics, was measured on basic plasma experiments, and molecular beam was discussed. The performance of the ion source is also critical in fusion devices. Studies of ion source for HIBP on LHD were reported. Production and transport of negative ions are discussed.

Interaction of plasmas and material (wall) is another focus in this ITC. The influence of wall material on the core confinement has been known phenomenologically; however, experimental study has not been systematic and only few theoretical efforts have been made. This ITC covers this important issue, including the discussion of the Li-wall effect on core confinement (TJ-II), the role of limiter on Gamma-10 confinement, and the observation of plasma wall interaction in steady state plasma. One of the most challenging problems in the plasma confinement is to understand the isotope effect on plasma confinement. Effect of hydrogen isotope (deuterium and hydrogen) was reported on TST2, and possible role of the interaction of neutral particles and wall was inferred.

Plasma material interaction stays at the center of key issues, in the design and performance of the divertor. Elementary process at divertor was reported, looking at issues of the chemical sputtering, heat load, etc., where basic experiment devices can have significant contributions. In parallel with the experimental measurement, direct simulations have also been in progress. Molecular simulations are reported by many authors. More realistic situation could be calculated not in far future.

8. Integrated Modelling

Based on the rapid progress in the understanding of essential processes of plasma dynamics, the integrated modeling has become more and more self-contained [16]. The integrated modeling becomes relevant, only if our understanding of each element is matured (Fig. 7).

Integrated modeling provides tests for theory, models and working hypothesis. This is the system, which accelerates the discovery of new phenomena, by integrating fragments of models, which cover elementary processes in particular scale-lengths. By use of the integrated modeling, we can identify the critical paths in our understanding or in the realization of devices. Considering these important roles of integrated modeling, two essential issues are

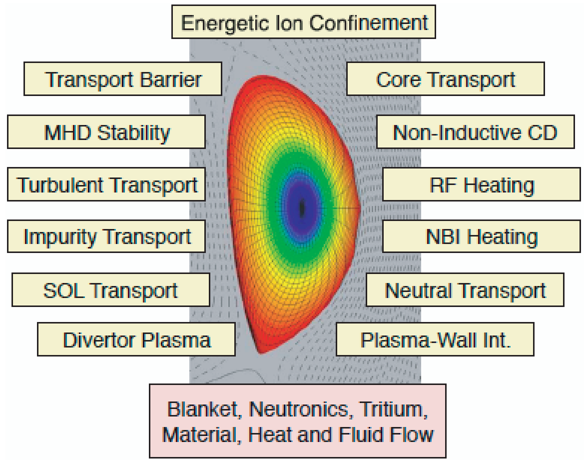

Fig. 7 Vision of integrated modelling (after Burning Plasma Simulation Initiative [16]).

noted here. One is the establishment of physics law (or at least models that is dependable in a certain range of parameters). The other is the structural scheme that integrates the models that cover limited range of plasma response.

A large number of progresses were reported on the application of 'TASK' in this ITC-19. Its extension to helical plasma, TASK-3D, has been applied to LHD plasmas routinely. Particular processes, such as role of zonal flow in transport barrier formation, pellet injection, divertor function, NBI source, application to Gamma-10 mirror plasma, and so on, were reported.

Introduction of advanced pictures for transport properties (nonlocal and statistical pictures, distant influence of wall material, mutual interaction with PAM physics, etc.) in integrated modeling is keenly waited for.

9. Problem Definitions for Reactor Studies

In the fusion research, advanced physics has had mutual interaction between reactor studies. The demands from reactor must be identified first, and then, must be compared to the capability of present method. This comparison provides problem definition for the future research.

Along this line of thoughts, the advanced scenario for DEMO was discussed taking an example of JT-60SA device. Another problem definition is the Component Test Facility, which is based on the spherical tokamak that may provide high performance for the volumic neutron source. In these studies, plasma physics and reactor development collaborate.

Studies of elementary processes in plasma dynamics, which are explained in chapters 2 to 8, were extended to the problem definitions for reactor study. For instance, neoclassical tearing mode control, radiation mantle, control of DT fuel ratio, access to ignition condition, confinement of fusion alpha particles, design of coils, dust divertor, and so on. FIRE-X project was discussed: Concrete example is different for inertial confinement fusion, but similar way of thinking in problem definition works.

10. Solar, Space and Astrophysical Plasmas

Solar, space, and astrophysical plasmas provide an arena where our understanding in theory and laboratory plasmas is synthesized.

New, detailed diagnostics accelerates our understanding of plasma dynamics at the sun. A flood of new knowledge was given from the observation by use of Hinode [11]. Much higher resolutions in space and time in observations have given new views of the solar corona dynamics. The reconnection and burst take place at smaller scales frequently, so that statistical picture is necessary to provide global understanding of bursts. Alfven waves are no longer theoretical object on the sun. Horizontal component of solar magnetic field was measured, which will give a clue in the modeling of solar dynamo.

Solar, space, and astrophysical plasmas stimulates researchers, and reports were made on: ion cyclotron emission and seismic phenomena, kinetic Alfven wave in solar wind, dispersive Alfven wave and disparate-scale interaction, particle acceleration by shock, and so on.

Those who are working on the laboratory plasmas can learn from the success in these observations of astrophysical plasmas. The list of difficulties in astrophysical observations is very long: the target plasma (say, the sun) is far away, data is sparse, interior is inaccessible, etc. Nevertheless, pictures and constructed models can be more precise in comparison with the laboratory plasmas. As is discussed in the chapter of advanced diagnostics, focused integration of diagnostic channels to an event, combined with e-science approach (such as turbulence diagnostic simulator) will provide more conclusive picture on the laboratory plasmas.

11. Nano-bio Plasmas

One of the most influential impacts of plasma physics on the present civilization is found in the plasma application to material procession. Knowing the fact that there is a bunch of articles that summarizes success of plasma applications, nano-bio plasma, in the realm of the plasma applications, merits special comment in the summary of ITC-19 [17].

One prototypical feature in the nano-bio plasma, which was highlighted in this ITC-19, is the fact that its study depends on the gas-liquid plasma interface. Thus, this research has strong analogy to the study of inhomogeneous plasma, barrier formation, etc. Biomaterials are easily treated in the liquid circumstance. Thus, the implantation of elements and of nano-material necessarily utilizes the plasma, which includes gas-liquid interface. The control of stability at the interface was reported to be the key in opening the new field of plasma physics.

In studying the process of interaction between cell and electromagnetic field, the frequency dependence was found in the selective interaction in the cell. The applied field is partitioned to membrem, nucleus, etc., and its division has sensitive dependence on frequency [18]. By selecting a proper range of frequency, the applied field is imposed selectively on the particular part of the cell. Such selective nature stimulates further studies of plasmas.

12. Further Extensions

Much more variety in plasma was reported in this ITC. Pair ion plasma, electron-positron pair plasma, plasma-dust structure, plasmon and scanning-near-field optics were discussed. Fractured powder and statistical theory fits to interest of some of participants. Non-destructive measurement of high-T_c conductors was discussed. Discussions of plasma jet sintering and plasma diode widened the varieties of application of methods extended in this ITC. I would like to stress here, again, that the variety of the issued discussed ITC-19 has relevance, because it demands the more universality in our understanding of plasma dynamics.

13. Few Words on Perspectives

In this summary report, a unifying viewpoint is chosen putting an emphasis on nonequilibrium physics of plasmas. The description of cross-field transport in toroidal confinement devices has developed to the nonlinear and nonlocal pictures. This picture is sheared by theory, simulation and experiments. Such common understanding in three methods of study shows a maturity of the research during the last two decades after the inauguration of NIFS. In the future ITCs, probabilistic picture of plasmas will show successes in understanding plasmas.

Several keywords are commented here. First, distinguished success will be achieved by researches that intend to identify causal relations (not only phenomenological relations) among observed quantities. Second, more and more focus will be required on the efforts to resolve central issues of ITER and fusion devices. Third, impacts on physics in general must be pursued, in order to visualize the value of plasma physics. Fourth, new plasma frontiers must be developed. These are examples of directions, in which substantial progress of achievements are highly plausible. One can learn from history about the progress of plasma physics. Figure 8 illustrates the evolution of number of published article in some journals, on the subject of the H-mode, zonal flow, and the toroidal rotation that is not induced by the external torque. Common in these samples is that the subject suddenly attracts wide attentions after a long lead time (precursor), which is order of a decade. Original and important work is usually performed during this precursor phase. This is the phase where the discovery of the problem and 'problem definition' are made. After

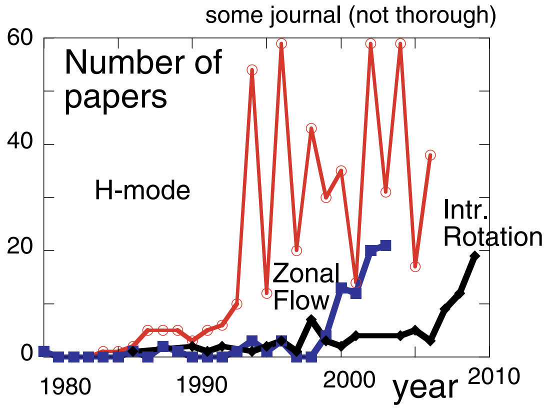

Fig. 8 Evolution of number of published article in some journals, on the subject of the H-mode, zonal flow and intrinsic toroidal rotation. (Journals are not exhaustive.)

the burst, the phase of 'solution and application' comes. There would arise the question 'which is more essential, the discovery or solution?' The answer depends on the style of researchers, and is left to reader's own judgement.

There are a lot of problems, for which research activities today are in the phase of precursor. They are waiting the future onset of bursts. We shall see onset of another burst on new problems in future ITCs.

14. Summary

The 19th International Toki Conference was held on the subject of advanced physics in plasma and fusion research. This summary is made with the perspective of 20 years of National Institute of Fusion Science after it inauguration. It is congratulated that unambiguous and distinct progresses have been made.

In the last decade, a paradigm shift in plasma physics occurred from 'linear, local and deterministic' picture to 'nonlinear, nonlocal and probabilistic' one. This change covers not only the theory and simulation, but also experimental observations. Integration of theory, simulation and experiment has been realized, and has been a primary motive force for advancing physics. This approach must be strengthened. Progresses have given solutions to problems, as was witnessed by audience in this ITC-19. At the same time, progress that had been achieved has identified clear problems that must be solved in future. In other words, we had not known what must be solved, but we have now much clearer view of what must be solved. Much research efforts must be spent in this direction, that is, more efforts must be made to *let knowledge evolve into understanding*. Further advancements will be reported in future International Toki Conferences.

Acknowledgements

Discussions with S. -I. Itoh, P. H. Diamond, A. Fujisawa, K. Ida, S. Inagaki, A. Fukuyama, R. Hatakeyama, N. Kasuya, M. Yagi and many colleagues are cordially acknowledged. This work was partially supported by Grant-in-Aid for Scientific Research (19360418, 21224014) of JSPS.

Dedication

This article is dedicated to Prof. Kyoji Nishikawa to celebrate his 77th year.

[1] Papers for presentations in ITC-19 are published in Plasma and Fusion Research (2010).
[2] F. Wagner, in *Second ITER International Summer School - Confinement*, AIP Conference Proceedings **1095**, 31 (AIP, 2009).
[3] J. G. Cordey *et al.*, Plasma Phys. Control. Fusion **36**, A26 (1994); U. Stroth *et al.*, Plasma Phys. Control. Fusion **38**, 1087 (1996); T. Iwasaki, S. Toda, S. -I. Itoh, M. Yagi, K. Itoh, Nucl. Fusion **39**, 2127 (1999).
[4] S. -I. Itoh and K. Itoh, Plasma Phys. Control. Fusion **43**, 1055 (2001).
[5] A. Komori, Plasma Fusion Res. 5, S2001 (2010); See also H. Yamada, in *Second ITER International Summer School - Confinement*, AIP Conference Proceedings **1095**, 178 (AIP, 2009); K. Ida, *et al.*, Phys. Plasmas **16**, 056111 (2009).
[6] P. H. Diamond, S. -I. Itoh, K. Itoh and T. S. Hahm, Plasma Phys. Control. Fusion **47**, R35 (2005).
[7] S. -I. Itoh, Plasma Fusion Res. **4**, 038 (2009).
[8] A. Fujisawa, Nucl. Fusion **49**, 013001 (2009).
[9] G. Zaslavsky, *Hamiltonian Chaos and Fractional Dynamics* (Oxford University Press, Oxford, 2005).
[10] See, e.g., O. D. Gurcan, P. H. Diamond, T. S. Hahm and Z. Lin, Phys. Plasmas **12**, 032303 (2005).
[11] See, for a survey of diagnostic systems of Hinode, S. Tsuneta *et al.*, Solar Phys. **249**, 167 (2008).
[12] H. K. Park *et al.*, Phys. Rev. Lett. **96,** 195003 (2006).
[13] R. M. Kulsrud, *Plasma Physics for Astrophysics* (Princeton Univ. Press, Princeton, 2005).
[14] T. E. Evans *et al.*, Nature Physics **2**, 419 (2006).
[15] G. Faussurier, R. M. More, C. Blancard and T. Kato, Phys. Rev. E **73**, 016407 (2006).
[16] A. Fukuyama, in *Second ITER International Summer School - Confinement*, AIP Conference Proceedings **1095**, 199 (AIP, 2009).
[17] R. Hatakeyama, T. Kaneko, W. Oohara, Y. F. Li, T. Kato, K. Baba and J. Shishido, Plasma Sources Sci. Technol. **17**, 024009 (2008).
[18] H. Akiyama, Parity **25**, 31 (2010) (in Japanese).