Chapter 1

Prof. Masahiro Wakatani and Fusion Research in His Days

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Prof. Wakatani has passed away on 9th January 2003 at the age of 57. It is a big tragedy that we have lost Prof. Wakatani. This article is to remember his achievements in fusion and plasma science.

1.1 Research period of Prof. Wakatani

Prof. Masahiro Wakatani (Fig. 3.7) was born on 15 May 1945, and was given the PhD degree from Kyoto University in 1973. He has worked at JAERI, IPP Nagoya University and PPL Kyoto University. He has been a full professor at Kyoto since 1985, (and on that occasion I have joined his chair as an associate professor to him). It was the thirty years, from 1973 to 2003, when he has played a leading role in fusion and plasma research.

Progress in the fusion and plasma research during these thirty years, from 1973 to 2003, can be seen in Fig. 1.1, which shows the starts of experiments of tokamaks and helical devices (stellarators). Each symbol corresponds to one experimental device. Devices are clarified into four: circular cross section (conventional) tokamaks (open circle), noncircular tokamaks (closed circle), helical devices (triangle), and spherical tokamaks (square). This figure clearly illustrates that the steady progress was first made on the circular cross-section tokamaks. Then the noncircular tokamaks are developed. In parallel, helical devices have been explored, slightly slower but steadily. In the fourth category, we observe that the spherical tokamaks have been attracting focused interest recently.

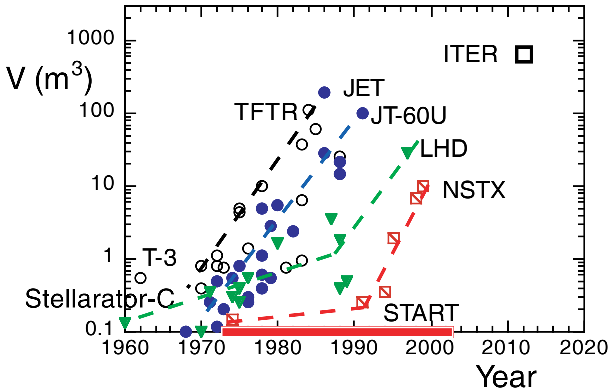

Fig. 1.1 Plasmas in the research period of Prof. Wakatani.

The research in the last three decades may be characterized by the following:

(1) the exploration of configurations was pursued,
(2) the tokamak plasma has been evolving to fusion regime,
(3) the optimization of toroidal systems was investigated,
(4) the plasma physics has been recognized as a frontier of general modern physics.

In particular, deeper and wider recognition of the fact that "the shape and size change the property of the matter in the confined plasma". Prof. Wakatani has provided many keys for the development in the above four aspects of the recognition in the fusion research.

Initial phase

An explicit goal of the fusion research has been to establish the scientific feasibility for the realization of controlled thermonuclear fusion. I would like to stress that, at the same time, our goal has been to systematize the research as a discipline. This latter goal has been recognized as important as the former, from the time of early 70s when Prof. Wakatani has started his academic carrier. For instance, we could quote from, e.g., Feynman Lectures on Physics, "The next great era of awakening of human intellect may well produce a method of understanding the *qualitative* content of equations. Today we cannot. Today we cannot see that the water flow equations contain such things as the barber pole structure of turbulence ···" [1].

It was 1974, when Prof. S. Yoshikawa, being collaborated by Prof. K. Nishikawa, has initiated "Workshop on Theoretical Research of Fusion" at Hachiouji near Tokyo. In the first and consecutive workshops, Prof. Yoshikawa has tried to establish a methodology for the research on confined plasmas in Japanese academic society. Those who have joined the series of this workshop, as a newcomer to this field then, have later grown up as leading researchers in Japan. Prof. Wakatani has been one of the leading figures in the series of the workshop.

Four examples from Prof. Wakatani's outstanding achievements

Prof. Wakatani's work has been always in the frontier of fusion research for the last three decades, which is illustrated in Fig. 1.1, and may be organized into four categories corresponding to the four characterization listed above.

The first is the problem of stability and plasma shape. The initial works are typical examples including the toroidal effect on vertical displacement of elliptic tokamak [2] and nonlinear calculation of the $m = 1$ internal kink instability in current carrying stellarators [3]. The second is the nonlinear instability problem, in which he proposed the so-called 'Hasegawa-Wakatani equations' [4]. This set of equations has been an elegant and elementary tool for theory and simulational studies of plasma turbulence. Thus, the influences of the plasma size and parameters on the turbulent transport have been clarified. The third, he has devoted continuously for understanding of helical systems [5] including the design study. In this area, he has developed a systematic theory of the stability of Heliotron systems, played a central role in the theoretical design of the large helical device (LHD) and also developed a helical axis system (heliac or helias). The fourth is the study of the structure formation in turbulent plasmas. By use of his 'Hasegawa-Wakatani equations' he has demonstrated that the global structures are generated by plasma turbulence [6].

It is evident that these four categories are the central issues in the fusion research of the last three decades as is illustrated in Fig. 1.1. In the next section, his originality is highlighted by selecting some of his leading achievements [7].

1.2 Research on nonequilibrium systems

In the research of complex phenomena in nonequilibrium systems, such as confined plasmas, it is essential to identify the appropriate equations. In particular, reduction of variables illustrates the physical processes and stimulates the finding of physics law. Prof. Wakatani has recognized this importance of selecting proper equations for proper problems, and has given illustrative results of key issues in confinement physics.

One example is his research on the relaxation phenomena in helical systems. Pressure driven relaxation instability in a current-free high-shear helical system has been studied by him and his students (e.g., [8]), and repetitive sequence of onsets of crash and following gradual recovery was shown by numerical simulation (Fig. 1.2). Thus he and his colleagues have opened the way that the nonlinear MHD dynamics of pressure-driven collapse events, which may limit the performance of helical devices, is treated quantitatively.

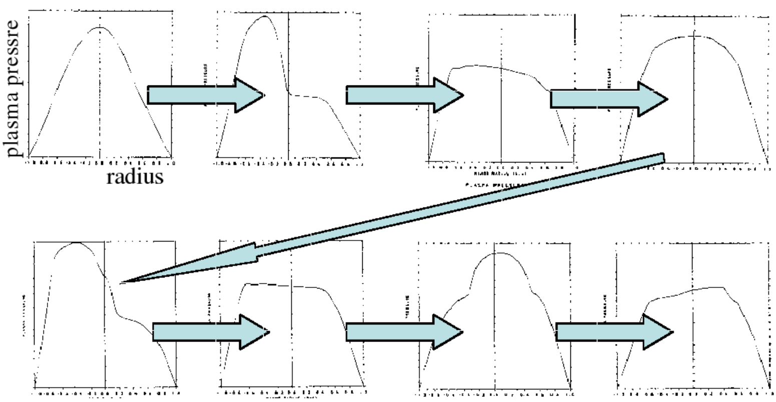

Fig. 1.2 Evolution of pressure profile in relaxation phenomena of Heliotron [8].

More famous example of his achievements is the investigation of the 'Hasegawa-Wakatani' equations.

$$\frac{\partial}{\partial t}\nabla_\perp^2\phi + \left[\phi, \nabla_\perp^2\phi\right] = d_\parallel\left(\phi - n\right) + \mu_c\nabla_\perp^4\phi \tag{1.1}$$

$$\frac{\partial}{\partial t}n + \left[\phi, n\right] = d_\parallel\left(\phi - n\right) - \frac{\partial\phi}{\partial y} + D_c\nabla_\perp^2 n \tag{1.2}$$

where $d_\parallel \equiv k_\parallel^2 v_{\mathrm{th},e}^2 \nu_{ei}^{-1}\omega_{ci}^{-1}L_n\rho_s^{-1}$. (Plasma parameters such as the density, temperature, characteristic scale of gradient, magnetic field are included into this one parameter $d_{\|}$.) This set of equations is simple, and includes the drive by instabilities and the process of generation of structures (such as zonal flow or convective cells, etc.). This is a prototypical set of equations which clarifies many of essential elements in the plasma turbulence, and has given tremendous impacts for the progress of physics for the confined plasmas. This has opened the area of research where mutual interactions between turbulence and meso-scale structure are studied. Two most important results are illustrated here. The first is the spectrum of plasma turbulence which is driven by inhomogeneity. When one talks about a generality of turbulent spectrum, many efforts have been devoted to the universality of the inertial regime [9]. It is true that, after the evolution of nonlinear turbulent interactions, external energy which is injected to a relevant scale is transferred to smaller scales and is finally dissipated by molecular collisions. In such a study to pursuit 'universality', the longer-wavelength components are often treated as external parameter. However, the longer-wavelength component contains dominant part of turbulent energies. Thus impact of turbulence to observable phenomena (or that to human recognition of nature) is mainly carried by the dynamics of the energy containing region. The determination of the energy spectrum in a region where free energy is injected by various instability mechanisms has vital importance. Such a problem needs a formulation a set of equations which include both the nonlinear dynamics of vortex together with instability mechanism. Thus, the Hasegawa-Wakatani equations have served the simplest set of equations, which provides insights for the evolution of turbulence. By use of this set of equation, Prof. Wakatani has obtained the spectrum

$$E(k) \propto k_{\perp}^{-3}, \tag{1.3}$$

where $E(k)$ is the energy spectrum [10]. This spectral form tells that the dominant part of turbulent energy is contained in the region of longest wavelength. The rate of the nonlinear transfer is summarized in the index, -3.

Another important finding is the flow generation by turbulence. Figure 1.3 is one early example [4], in which the formation of potential contour, loosely resembling that of the magnetic surface, is demonstrated. These contour structures indicate the presence of banded poloidal $E \times B$ flow, called zonal flow. It has been pointed out that in the two-dimensional turbulence, the turbulence energy can cascade, not only into the finer scales, but also in the direction of longer scale lengths. As the injection of energy to a mode continues, the wave energy starts to pile up in the longer-wavelength region if the molecular dissipation is weak. Turbulence in toroidal plasmas is quasi-two-dimensional owing to the strong magnetic field. The Hasegawa-Wakatani equations are formulated in a form of two dimensional turbulence, where the wavenumber in the direction of magnetic field is treated as a constant parameter. The accumulation of wave energy in the longer wavelength region is demonstrated by the simulation of the Hasegawa-Wakatani equations. As is seen from Fig. 1.3, the potential contour is akin to the magnetic surface. This means that the fluctuation electric field in the poloidal direction is weak, i.e., the fluctuating velocity in the radial direction is small. Thus, the reduction of radial transport is expected to occur when such a global electrostatic potential is established. It is well known now that the studies of the improved confinement in 90's are developed based upon several key ideas, such as the suppression of turbulence by radial electric field, bifurcation of the radial electric field, and the formation of zonal flow by turbulence [11]. All of us are aware of the leading role of Prof. Wakatani's work in the progress of the theory of plasma confinement.

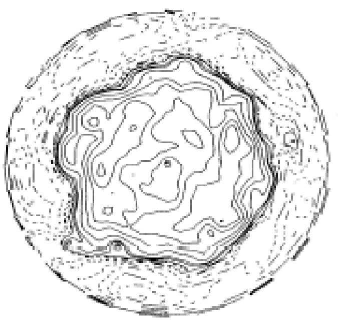

Fig. 1.3 Contour of electrostatic potential from the simulation of [4].

We could now enlighten his work as a historical achievement. We recall Helmholtz's theorem, i.e., vortex lines move with fluid (in invicid fluid). In a terminology of plasma physics [12] one may express the evolution of the vorticity as

$$\frac{\partial}{\partial t}\nabla_{\perp}^{2}\phi + \left[\phi, \nabla_{\perp}^{2}\phi\right] = \cdots \tag{1.4}$$

The Helmholtz theorem tells that the RHS vanishes, $\cdots = 0$. In the nature, however, there are abundant of examples that the vortical flow structure is 'generated'. More generally, the global axial vector fields are generated by the turbulent convection of thermal energy. Such as, geodynamo, solar dynamo, Jet formation in accretion disk, Jovian zonal flow, Jet stream, Venus super rotation, etc. In the problems of plasma structure formation, one can point out the relaxation to Taylor state, sawtooth oscillation, H-mode, ITB, zonal flow, dynamo, etc. These phenomena will be explained if "$\cdots$" in the right hand side of this equation is properly modelled. In this aspect, Prof. Wakatani has given a critical step for the development of general physics.

Prof. Wakatani has thus clarified an essence of the problem. This attitude of him was described as "$\cdots$ Perhaps because Wakatani-sensei lived in the ancient cultural region of Kyoto and Nara, he liked theories that were simple, orderly, and yet elegant, like a Zen garden. $\cdots$" by Prof. J. W. Van Dam and Prof. C. W. Horton, Jr. in the tribute to Prof. Wakatani. Looking into waves of pebbles in Zen garden, one may see waves, tide and vortices in nature.

1.3 Wakatani-sensei's gifts to scientists

There are a lot of key elements in order to promote the future progress. Among them, Prof. Wakatani has contributed much in the following aspects:

(1) Systematization of achievements as a branch of academic research,
(2) Improve creativity,
(3) Improve environment of research.

What he has done in relation to these issues is now considered as a gift from Prof. Wakatani to the future researchers.

Systematization of research results as an academic discipline

What should be emphasized first is that, Prof. Wakatani has been an excellent teacher for the students. Education of students was a joy for him, and his devotion to the education has been awarded by the energetic scientific production by those in Wakatani school. They are now central members in the theory and simulation researchers in Japan.

In relation with the education, he has also made efforts in publication of books. The achievement includes: "The Beta Equilibrium Stability and Transport Codes: Applications to Design of Stellarators" by F. Baure,

O. Betancourt, R. Garabedian, M. Wakatani (Academic Press, Inc., 1987); "Plasma Physics Basic Theory with Fusion Applications" by K. Nishikawa, M. Wakatani (Springer-Verlag, 1990 (Second ed. 1993, Third ed. 1999)); and "Stellarator and Heliotron Devices" by M. Wakatani (Oxford University Press, 1998). The fact that the third edition of his "Plasma Physics Basic Theory with Fusion Applications" was published shows that this book is widely accepted by the international academic community.

Improve creativity

Next, he played a role in improving the creativity of researchers. I would point out three keys. "Increasing creativity" might be heard as a miracle, but what Prof. Wakatani has done has been full of the essence for it.

The first key for the creativity is 'Self-belief'. Without self-belief, one cannot achieve a really new scientific achievement on which nobody has thought or analyzed. Only by the self-belief, we can continue the work until the final breakthrough is realized. Prof. Wakatani has been always encouraging his colleague and students. By warm encouragement by him, many researchers have been injected self-belief.

The next key is 'chemistry' among researchers. From the time of ancient peripatetic school at Greek, to the modern Copenhagen spirit, and to recent group researches, the communication between many researchers has been the central scheme for driving creative ideas that had shed lights for human understanding. In the area of fusion and plasma research, Prof. Wakatani has been always leading friendship among researchers. He has been always stressed 'loose-coupling' among scientists: this was the key of him so that researchers keep good chemistry among them while each of the members can grow their own originality.

Third, his efforts to grow the chemistry has been most impressive in his contribution in the international collaborations. Interactions between different ways of thinking, no doubt, is the key for the emergence of the new idea. For this, the interactions between Oriental-Occidental ways of thinking, as well as International and Interdisciplinary way of thinking, are very effective way of progress. Wakatani-sensei's efforts have covered many endevours, e.g., IUPAP (plasma physics), US-Japan collaboration on fusion research, in particular Joint Institute for Fusion Theory, International Stellarator Workshop, International Toki-conference, Festival de Theorie, and others. Every participant in the first Festival de Theory remembers Wakatani-sensei's warm and leading work in the festival (see Fig. 3.8).

Improve environment of research

Prof. Wakatani was the leader in Japanese education for plasma and fusion science. He was elected as councilor of Kyoto University, and everyone has believed that he would soon be a dean. He was the key promoter for the 21st Century COE (center of excellence) Program of MEXT (ministry of education, culture, sports, science and technology) on "Establishment of COE on Sustainable-Energy System". For this, he was the task leader for "Plasma Group", and provided a splendid conditions for researcher who belonged to this programme. He has also made a lot of efforts for academic agreement between Kyoto U. and Universite de Province and others.

His devotion benefited the communication between the scientists, government officials and citizens. He was a member of Fusion Council of Japan, which was the highest subcommittee specializing at the national policy of the fusion research. He was also a subcommittee member of Science Council of Japan, in which academic society has shown opinions to the government. Prof. Wakatani has played a role of spokesman for the researchers in the field of plasma and fusion study to the government and to wider academic society.

Among these activities, his role for the big project ITER was outstanding. He was a member of Technical Advisory Committee, and was the chairman for scientific and technical evaluation of ITER for Fusion Council of Japan. Through these activities, he guided Fusion Council of Japan to have scientific judgement for the decision of participating the ITER project.

In the end of this article, let me be a bit sentimental. We had started an activity of "Group of Seven" since 1985. Members were (in alphabetical order) M. Fujiwara, K. Itoh, S.-I. Itoh, S. Matsuda, O. Motojima, Y. Shimomura and M. Wakatani. At that time, foreseeing the start of the LHD project, an endeavour to make an inter-institutional research collaboration project in Japan has been studied. One of the first outcome of this activity was 'Method for design of Large Helical Device'. It strengthened the spirit of collaboration, domestic as well as international, which has been the essence of Wakatani sensei's research moral.

1.4 Closing words

All of us have been impressed by his dedication to the science, students, colleague, academic society and, last but not least, his family. The enlightening ideas and selfless devotion for research have sprung from his heart.

Prof. Wakatani's spirit lives with us so long as the plasma physics and fusion research continue to evolve.

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