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Contributions of Masahiro Wakatani to the Study of MHD Properties of Magnetically Confined Plasmas and to the Understanding of Helical Systems

CARRERAS Benjamin A.
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, U. S. A.

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Abstract

During his professional life, Masahiro Wakatani made multiple contributions to understanding the physics of magnetically confined plasmas. A major area of research was nonlinear magnetohydrodynamics. He, directly and through many of his students, made significant contributions to this area, particularly in the dynamics of resistive interchange, tearing, and internal kink instabilities in helical systems. Modeling of the sawtooth oscillations in stellarator/heliotron devices and the study of the beta limits may be some of his main achievements. Prof. Wakatani spent a great deal of time on the study of helical systems, and he played an important role in the physics design of the Large Helical Device and Heliotron J.

Keywords:

magnetohydrodynamic, helical system, internal disruption, sawtooth oscillation

1. Introduction

Professor Masahiro Wakatani's contributions to plasma physics spanned a period of about 30 years. With more than 230 publications, he has left his mark on many different areas research. His interest in helical systems was central to most of his work, but his research was not limited to those confinement systems. To follow his work over those years is to follow the history of plasma physics during that period of time. He has been involved with most of the dominant topics of this field, and his contributions have been extensive.

In this paper, I will concentrate on two aspects of his research, magnetohydrodynamics (MHD) studies and the physics of helical systems. His contributions to transport and kinetics will be reviewed in another paper presented at this meeting [1]. Even by focusing on these two topics, it would not be possible for me to cover all his work in a short paper. Therefore, I will select a few aspects of his research that I feel more significant and will provide just a brief glance at his work.

The rest of the paper is organized as follows. In Sec. **2**, I look at the historical background of MHD studies during the 1970s, when professor Wakatani started his research, and I review some of his work on nonlinear MHD applied to tokamaks. In Sec. **3**, I describe his research in the 80s, when his MHD studies were centered on the currentless operation of helical systems. In the late 80s, Wakatani's research moved toward the physical design of the next generation of helical systems, the Large Helical Device (LHD) and Heliotron J. These studies are described in Sec. **4**. In Sec. **5**, I consider one of the most interesting contributions, the flow self-organization in plasmas and subsequent work on the effect of flows on MHD instabilities. Finally, in Sec. **6**, I present the conclusions of this paper.

2. MHD activity in tokamaks: late 70s

In the 70s, two main experimental issues dominated MHD research: sawtooth oscillations and major disruptions. The results of the soft X-ray measurements made in 1974 in the Princeton Large Torus (PLT) [2] showed the existence of sawtooth-like relaxation oscillations at the tokamak core, which were linked to an $m = 1$ precursor oscillation. This experiment started intense experimental and theoretical research activities that cover more than a decade.

The concern over major disruptions started earlier. From the first tokamak experiments [3], major disruptions were perceived as a serious handicap for the long-term performance of tokamaks. Therefore, understanding disruptions became a high priority in the fusion program. In the 70s, research activity in disruptions was high. Numerous papers on this topic were published in the proceedings of the International Atomic Energy Agency (IAEA) meetings in 1974 and 1976. The soft X-ray diagnostic in the PLT offered one of the first

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Corresponding author's e-mail: carrerasba@ornl.gov detailed views of a major disruption process [4]. Here, I am more interested in picking up the role of helical systems in the control of a major disruption. In an interesting paper by the Wendelstein VII A group [5], the control of the $m = 2$ mode by helical winding was discussed in detail. Previous results from Pulsator indicated the suppression of the $m = 2$ mode by helical winding, but the W-VII A results had detailed profile documentation. These types of studies were probably the most significant contributions to the understanding of helical systems at that time.

In trying to identify the mechanism for the sawtooth oscillations, theoretical researchers started identifying possible $m = 1$ instabilities for a tokamak. In 1970, Shafranov [6] classified the ideal current-driven instabilities in a straight cylindrical system. In principle, the internal kink mode was a good candidate to explain the sawtooth oscillations. However, the linear growth rate of this instability in cylindrical geometry was too high compared with the experimental growth, and the internal kink nonlinearly saturates at finite amplitude [7]. The saturation is caused by a shift of the magnetic surfaces and by the formation of a sharp current sheet in the region of compressed flux surfaces. This process saturates the instability without causing any magnetic reconnection. Furthermore, it was later shown [8] that the internal kink is stable in a toroidal geometry. Therefore, it was necessary to look for other explanations for the precursor oscillations.

At that time, other possible candidates for the precursor oscillations were the $m = 1$ tearing mode [9], with the linear growth rate scaling as $\gamma \approx S^{1/3}$ and the $m = 1$ reconnection mode, with $\gamma \approx S^{3/5}$ [10]. Here, S is the Linquist number. In 1976, Kadomtsev [11] suggested some possible reconnection mechanisms that would explain the relaxation process independent of the particular instability.

Numerical calculations offered an approach to resolve some of the pending issues in the interpretation of the experimental results [12-14]. However, the limited computer capabilities did not allow making high-resolution calculations in a toroidal geometry, and calculations done for a cylindrical geometry did not allow an independent understanding of the different $m = 1$ instabilities. In particular, at low beta and in a cylindrical geometry, the internal kink is marginally stable and the tearing mode has a faster growth than the reconnection mode.

This was the research background when Professor Wakatani started his own research. Wakatani took an interesting approach to the numerical study of the $m = 1$ instabilities [15,16]. In a cylindrical geometry, he used external windings to change the properties of these instabilities. Given the stellarator expansion [17] for low-β plasmas, the effect of helical windings comes essentially through the rotational transform, $\iota(r) = \iota_\sigma(r) + \iota_{ext}(r)$, where $\iota_\sigma(r)$ is the rotational transform due to the current and $\iota_{ext}(r)$ is the one induced by the helical windings. Therefore, the use of the external magnetic field decouples the rotational transform from the current profile. By varying $\iota_{ext}(r)$ one can change the stability properties of the $m = 1$ instabilities. For $d\iota_{ext}/dr < 0$, the internal kink mode can be unstable and the reconnection mode is stable. However, for $d\iota_{ext}/dr > 0$, the internal kink mode is stable and the reconnection mode can be unstable. In both cases, the tearing mode can be unstable.

Wakatani used stellarator expansion to derive a nonlinear reduced set of MHD equations for low-β plasmas. He used these equations and varied the external rotational transform to carry out numerical calculations in the different regimes. In this way, he was able to study the nonlinear properties of these different $m = 1$ instabilities. In his work, Wakatani confirmed the analytical results of Rosenbluth, Dagazian, and Rutherford [7] on the saturation of the internal kink mode. He also studied the nonlinear evolution of the $m = 1$ tearing mode when both the ideal kink and the reconnection mode are stable. First, the $m = 1$ tearing mode induces a magnetic island in the plasma that grows at a fast rate. This evolution causes a reconnection through the magnetic axis, and the magnetic configuration goes back to being axisymmetric. This second reconnection causes the loss of energy responsible for the relation oscillation. This mechanism had already been shown [12-14] and was the standard interpretation of the sawtooth oscillations. He was also able to study the nonlinear evolution of the reconnection mode. There were no nonlinear calculations of this instability at that time. Wakatani showed that this mode has an initial slow growth (Rutherford regime) followed by a fast evolution, similar to the nonlinear evolution of the resistive kink mode.

3. Stellarator currentless operation: the 80s

Helical systems took a significant step forward in the early 80s. The first results of currentless operation were obtained in both W-VII-A [18] and Heliotron E [19]. This ability to operate with zero net current changed the potential role of helical systems as confinement systems. Therefore, researchers quickly moved to explore their confinement capabilities. This change had a strong impact in the MHD studies; they turn to calculation of beta limits for helical systems, nonlinear behavior of pressure-driven instabilities, and analysis of the new experimental results. Wakatani was deeply involved in all these activities.

In the early 80s, Wakatani used the stellarator expansion to derive a linear set of MHD equations incorporating finite β effects [20]. He used these equations to study the ideal interchange and ballooning stability properties of Heliotron plasmas. He showed that the critical β effects depend sensitively on the pressure profiles. In particular, for the $n = 1$ mode, the pressure gradient at the $\iota = 1$ surface is a critical parameter. He found values of $\beta_c(0)$ in the range of 5.2 to 6.8%, depending on the profile. These results were similar to other calculations carried out at this time [21, 22].

Investigation of ideal and resistive instabilities continued over the years of operation of Heliotron E. New codes were developed or adapted by Wakatani and collaborators for these studies. For instance, the 3-D BETA code [22] developed at the Courant Institute was used in the study of the $m = 1/n = 1$ instability [23] and in the study of helical axis configurations [24]. The new STEP code developed at Princeton and based on stellarator expansion was applied to study the effect of the profiles on stability [25]. From all this research, a better understanding was gained of the Heliotron E β limits and of the parameters affecting plasma stability. Also, new instabilities were discovered, such as the nonresonant resistive instabilities near the magnetic axis [26].

Because of the renewed interest in helical systems, there was a great push forward in the development of new computational tools for MHD studies. Comparative studies of the different codes were carried out, and Wakatani and his collaborators were at the center of these activities [27].

As the high-β regime was explored, helical systems started to develop a rich phenomenology of MHD activity. Interpretation of the experimental results became one of Wakatani's main research activities. When internal disruptions were observed in Heliotron E, he revisited some of the nonlinear calculations of internal kink instability but used an external rotational transform that corresponded to Heliotron E. The internal kink evolution followed the basic saturation pattern obtained by Rosenbluth et al. [7], but once the shifted surfaces were compressed, finite resistive effects became important and a full reconnection took place [28].

In 1984, measurements of relaxation oscillations made at Heliotron E were reported [29] that were clearly affected by the increased injection power in the machine. Mirnov loops also identified $m = 1$ precursor oscillations. These sawtoothing discharges led to a soft β limit for Heliotron E. However, by using a gas puff during the neutral beam injection, a quiet mode was produced with β values up to $\langle\beta\rangle \sim 2\%$. This quiet mode offered a stable path to high β. Clearly, the experimental results indicated the importance of the pressure profile, here controlled with gas puff, in reaching high β. This profile dependence was expected because of results from previous MHD studies. However, it was necessary to do more detailed calculations in order to understand the sawtoothing phenomenon and the stable path to high β.

Wakatani et al. [30] carried out a series of calculations of the nonlinear evolution of the $m = 1/n = 1$ resistive-pressure-driven instability with pressure profile evolution (heating and transport). They used a reduced set of nonlinear MHD equations that incorporated finite β effects. In those calculations, the evolution of the $m = 1/n = 1$ resistive-pressure-driven instability led to a magnetic island formation, followed by a reconnection leading to two magnetic islands. When the pressure profile was evolved, it led to relaxation oscillations with peak beta oscillating between 2.3% and 3.3%. This model explained the experimental observations in Heliotron E.

Professor Wakatani did more than interpret experimental results; he also helped to plan experiments in order to test some of the basic ideas resulting from the MHD calculations. He designed experiments for Heliotron E to test stability properties of interchange modes by modifying some of the basic parameters controlling their stability properties. This was done by changing the magnetic field induced by vertical field coils and toroidal coils. The vertical field coils, by shifting the magnetic axis, change the magnetic well, while the toroidal field coils change the rotational transform and the plasma size. These tests are not simple because both MHD properties and confinement properties are changed, and they work often against each other. The moderate β results were found to be consistent with the MHD calculations [31].

4. Design and operation of new helical experiments: late 80's and 90's

The experience gained from the W-VII, Heliotron E, Advanced Toroidal Facility (ATF), the Compact Helical System (CHS), and other devices gave credibility to the MHD stability calculations for helical systems. When the decision about the next generation of stellarators emerged, MHD tools were available for detailed physics studies and for optimization of the new experiments. In Japan, the next-generation device was LHD, now in operation at the National Institute for Fusion Science (NIFS). Wakatani and his collaborators actively participated in the physics evaluation of the LHD [32] and in the development of the physics basis [33] to decide the basic parameters of the device.

In the early 90s, the planning process began for a successor experiment to Heliotron E. Wakatani and his collaborators [34] developed a low-aspect-ratio four-field-period concept, which was a hybrid of a Helias and a Heliac. In the design, they used an $l = 1$ pitch-modulated continuous coil to create the helical field. As characteristic of heliotrons, a set of toroidal field coils was added to control the rotational transform. These coils also provided a bumpy field that can be used to study improvement of the neoclassical transport. Optimization studies followed, and the concept evolved through a series of physics studies [35-39]. The final form of this concept [40] led to the Heliotron J device, the goal of which is the study of helical axis configurations. Heliotron J is now in operation at Kyoto University.

In the 90s, the CHS was in operation, and later on, the LHD was started. Wakatani was involved in the interpretation and modeling of some of the experimental results from these devices. One of the questions to which he dedicated time was the apparent violation of the Mercier criterion [41]. This was not a new issue, but it is always difficult to test because of the high accuracy required in the determination of the plasma equilibrium. One way of improving the Mercier stability is by including the effect of net currents [42]. Because the bootstrap current may play a role in the high β plasmas, it has been pursued to understand the experimental measurements. An alternative approach is to consider the effect of local flattening of the pressure profile at a rational surface [43]. The research continued investigating the stability of pressure profiles with flat spots at several low rational surfaces for plasma parameters close to LHD parameters [44] and the self-organization of profiles by resistive interchange dynamics that leads to such staircase-like pressure profiles.

Another topic of research that was motivated by the LHD experimental results is the effect of collisionality and β on the size of magnetic islands [45]. A model was developed based on magnetic islands induced by resistive interchange dynamics. Initial results [46] indicate that this model is consistent with experimental results.

5. Flow effects on MHD stability

In this quick review of the MHD research activity of Masahiro Wakatani, let us go back in time to pick up a very interesting topic that overlaps with his transport and turbulence studies. In 1987, Hasegawa and Wakatani published a paper [47] based on the 3-D turbulence calculations of resistive-interchange instabilities that showed the self-organization of flows and turbulence. In that paper, they show that electrostatic turbulence self-organizes to form a macroscopic potential ϕ (flow stream function), which is only a function of the radial coordinate. A feature of this potential is the existence of a surface with $\phi = 0$. This surface inhibits radial particle transport. The paper anticipated much of the work that was done in the 90s on flow generation and turbulence suppression, which are the basic mechanisms for models of transition to enhanced confinement regimes.

This result also has implications for MHD stability. Some MHD instabilities can lead to generation of global flows by Reynolds stress, in a very similar way as the electrostatic turbulence did. These flows can affect the stability of the same MHD modes and can lead to self-organization. Wakatani and collaborators carried out an investigation of some of these effects during the 90s. In some cases, instabilities are suppressed by sheared flows. This is the case for resistive interchange modes [48]. Flows with moderate shear cause a stabilization of these modes. However, for highly sheared flow levels, the Kelvin-Helmholtz instability can be destabilized. In Heliotron E, these modes can be destabilized if the poloidal flow shear is large enough. The main saturation mechanism is the quasi-linear modification of the poloidal shear-flow profile [49]. There is transfer of energy from low-*m* to high-*m* modes, where energy is dissipated. This transfer of energy contributes to the saturation of the instability, but its overall effect is small. The saturation level depends only weakly on resistivity and viscosity.

Flows may also have a destabilizing effect on very narrow modes as the ideal modes interchange [50]. A modified version of the Suydam criterion shows the general destabilizing character of the sheared flow for these instabilities.

6. Conclusions

Masahiro Wakatani had a productive professional life. He contributed fundamentally to making helical systems good confinement devices, and his work has shed a great deal of light on MHD and transport in plasma physics. His contributions will be remembered for years to come.

He educated and influenced a large number of students, many of whom are now strong contributors to plasma physics research. These students and all other researchers who had the pleasure of working with him will carry on his legacy. He was an example for all and a good friend.

For me, the main lesson from his life is that one can be a good researcher and a successful professional and still remain a very nice and good person.

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References

[1] J. Van Dam, paper at this conference.
[2] S. Von Goeler *et al.*, Phys. Rev. Lett. **33**, 1201 (1974).
[3] E.P. Gorbunov *et al.*, Sov. J. At. Energy **15**, 1105 (1963).
[4] N. Sauthoff *et al.*, Princeton Plasma Physics Laboratory Report No PPPL-1379, 1978.
[5] W-VII-A Stellarator Team, *in Controlled Fusion and Plasma Physics, Proc. 8th Europ. Conf.*, Prague, 1976, Vol. 1, 127 (1976).
[6] V.D. Shafranov, Sov. Phys.-Tech. Phys. **15**, 175 (1970).
[7] M.N. Rosenbluth *et al.*, Phys. Fluids **16**, 1894 (1973).
[8] M.N. Bussac *et al.*, Phys. Rev. Lett. **19**, 1987 (1975).
[9] H.P. Furth *et al.*, Phys. Fluids **16**, 1054 (1963).
[10] B. Basu *et al.*, Nucl. Fusion **17**, 1245 (1977).
[11] B.B. Kadomtsev, Fiz. Plasmy **1**, 710 (1975).
[12] B.B. Kadomtsev, Sov. J. Plasma Phys. **2**, 533 (1976).
[13] A. Sykes *et al.*, Phys. Rev. Lett. **37**, 140 (1976).
[14] B.V. Waddell *et al.*, Nucl. Fusion **16**, 528 (1976).
[15] M. Wakatani, Nucl. Fusion **18**, 1499 (1978).
[16] M. Wakatani, Nucl. Fusion **19**, 1235 (1979).
[17] J.M. Greene *et al.*, Phys. Fluids **4**, 875 (1961).
[18] W-VII-A Team, *in Plasma Physics and Controlled Fusion, Proc. 9th Int. Conf.*, Baltimore, 1982, *published by* IAEA, Vienna, Vol. 2, 241 (1983).
[19] A. Iiyoshi *et al.*, Phys. Rev. Lett. **48**, 745 (1982).
[20] M. Wakatani, IEEE Trans. Plasma Science, ps-**9**, 243 (1981).
[21] H.R. Strauss *et al.*, Phys. Fluids **24**, 1148 (1981).
[22] F. Bauer *et al.*, Phys. Fluids **24**, 48 (1981).
[23] M. Wakatani *et al.*, Nucl. Fusion **26**, 1359 (1986).
[24] K. Ichiguchi *et al.*, Nucl. Fusion **28**, 411 (1988).
[25] G. Rewoldt *et al.*, Plasma Phys. Control. Fusion **29**, 1643, (1987).
[26] K. Ichiguchi *et al.*, Nucl. Fusion **31**, 2073, (1991).
[27] Y. Nakamura *et al.*, J. Comput. Phys. **128**, 43 (1996).
[28] M. Wakatani *et al.*, Nucl. Fusion **23**, 1669 (1983).
[29] J. Harris *et al.*, Phys. Rev. Lett. **53**, 2244 (1984).

[30] M. Wakatani *et al.*, Nucl. Fusion **24**, 1407 (1984)

[31] M. Wakatani *et al.*, *Proceedings of the 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, 1990, *published by* IAEA, Vol. 2, page 567, 1991.

[32] Y. Nakamura *et al.*, Fusion Tech. **19**, 217 (1991).

[33] J. Todoroki *et al.*, *Proceedings of the 12th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, 1988, *published by* IAEA, Vol. 2, page 637, 1989.

[34] M. Yokoyama *et al.*, Nucl. Fusion **34**, 288 (1994).

[35] M. Yokoyama *et al.*, J. Plasma and Fusion Research **70**, 542 (1994).

[36] T. Matsumoto *et al.*, J. Phys. Soc. Jpn. **64**, 4175 (1995).

[37] M. Yokoyama *et al.*, Fusion Tech. **27**, 186 (1995).

[38] M. Yokoyama *et al.*, J. Plasma and Fusion Research **73**, 723 (1997).

[39] M. Yokoyama *et al.*, Nucl. Fusion **40**, 261 (2000).

[40] M. Wakatani *et al.*, Nucl. Fusion **40**, 569 (2000).

[41] S. Okamura *et al.*, Nucl. Fusion **39**, 1337 (1999).

[42] K. Ichiguchi *et al.*, Nucl. Fusion **33**, 481 (1993).

[43] T. Tatsuno *et al.*, Nucl. Fusion **39**, 1391 (1999).

[44] K. Ichiguchi *et al.*, Nucl. Fusion **41**, 121 (2001).

[45] N. Ohyabu *et al.*, Phys. Rev. Lett. **88**, 055005 (2002).

[46] L. Garcia *et al.*, Nucl. Fusion **43**, 553 (2003).

[47] A. Hasegawa *et al.*, Phys. Rev. Lett. **59**, 1581 (1987).

[48] H. Sugama *et al.*, Phys. Fluids B **3**, 1110 (1991).

[49] Y. Ishii *et al.*, Plasma Phys. Control. Fusion **36**, 2045 (1994).

[50] K. Watanabe *et al.*, Nucl. Fusion **32**, 1647 (1992).