Reviews of Modern Plasma Physics (2023) 7:21
https://doi.org/10.1007/s41614-023-00123-6

HISTORY

# Sanae-Inoue Itoh 1952–2019: a memorial note for a pioneer researcher of plasma bifurcation

**A. Fujisawa**[1,2] · **N. Kasuya**[1,2] · **Y. Kosuga**[1,2] · **Y. Nagashima**[1,2] · **M. Sasaki**[4] · **T. Yamada**[2,3]

Received: 10 August 2022 / Accepted: 30 April 2023 / Published online: 31 May 2023

## Abstract

This memorial note for Professor Sanae-I Itoh presents her specific achievements in physics research alongside her wider record of accomplishment in the field of magnetically confined plasmas. The topics include bifurcation phenomena (e.g., H-mode and improved confinement modes), turbulence-generated structures (e.g., zonal flows and streamers), and fundamental concepts and processes in plasma turbulence (e.g. nonlinear couplings and energy transfer. The note focuses initially on results obtained through her integration of theory, simulation, and experiment, particularly those arising from a low temperature plasma facility at Kyushu University. We then describe contemporary challenges in plasma turbulence which Sanae addressed with great interest, and consider some of the perspectives that were opened by her achievements.

**Keywords** Plasma turbulence · Bifurcation · Radial electric field

## 1 Introduction

During the past half century, there has been substantial progress in obtaining and understanding the high-performance plasmas that are necessary for nuclear fusion (Gibney 2022; Clery 2021, 2022; Tollefson and Gibney 2022). The conditions

---

✉ A. Fujisawa
fujisawa@riam.kyushu-u.ac.jp

[1] Research Institute for Applied Mechanics, Kyushu University, 6-1, Kasuga Kohen, Kasuga, Fukuoka 816-8580, Japan

[2] Research Center for Plasma Turbulence, Kyushu University, 6-1, Kasuga Kohen, Kasuga, Fukuoka 816-8580, Japan

[3] Faculty of Arts and Science, Kyushu University, 744 Motooka, Nishiku, Fukuoka 819-0395, Japan

[4] College of Industrial Technology, Nihon University, 1-2-1 Izumi-cho, Narashino, Chiba 275-8575, Japan

required for a burning plasma have been largely achieved, and the next generation of experimental facilities will exploit this progress systematically. Plasma turbulence is among the key physics challenges on this journey, raising questions and intriguing phenomena that are also important elsewhere in contemporary physics: for example, structural bifurcation, non-local property of transport, turbulence generated structures. Prof. Sanae-I. Itoh was one of the great plasma physicists who challenged these mysteries in the research field of magnetic confinement plasma. Many of Sanae's results were obtained in collaboration with her husband and long-term research partner Prof Kimitaka Itoh [whose obituary of Sanae was published in PPCF (Itoh 2020)], and with an extensive network of colleagues internationally and within Japan. Amongst her physics achievements, the most famous one is the first proposal of a theory that reminds us of the significant importance of radial electric field, $E_r$ and its nature of bifurcation (Itoh and Itoh 1988; Ida et al. 1990; Fujisawa 1997) after being inspired by the discovery of H-mode transition by Prof. F. Wagner and colleagues (Wagner et al. 1982). Moreover, she pushed forward her research, always indicating new directions and advanced concepts in understandings of turbulent plasmas (Itoh and Itoh 1996), i.e., self-sustained nature of plasma turbulence, turbulence suppression related to electric field structure (Itoh et al. 1994a), abrupt events often accompanied with collapses (Itoh et al. 1991, 1998), physics of zonal flows and streamers (Diamond et al. 2005; Fujisawa et al. 2004, 2007; Inagaki et al. 2011), and developing tools for plasma turbulence research (Nagashima et al. 2005; Itoh et al. 2005). Furthermore, she promoted her own integrated project, called Itoh project, in which theory has initiative on simulation and experiment. Particularly, she constructed her own experimental facility at Kyushu University, having noted the excellent potential of low temperature plasma for turbulence research, to produce various fundamental results (Yamada et al. 2008; Inagaki et al. 2016). This memorial note, focusing largely on the work of Sanae Itoh, provides a brief description of her above-mentioned achievements and associated work alongside her research progress. Section 2 introduces theories for H-mode and improved confinement, as well as their experimental confirmations, while Sect. 3 focuses on the physics achievements internationally in her own project (or Itoh project), with ones obtained in her constructed facility. Concluding remarks are placed in Sect. 4, where we discuss the unsolved problems of contemporary physics, relevant to plasma turbulence, in which Sanae took great interest.

## 2 Physics of H-mode and improved confinement

### 2.1 H-mode and improved confinement

The H mode was discovered in ASDEX tokamak for the first time in 1982 (Wagner et al. 1982). The significance of H mode was to demonstrate that toroidal plasma can bifurcate, and that the plasma confinement can be improved above a heating power threshold. The latter gave a strong impact to fusion research at the time when the problem was a phenomenon, so-called power degradation, as empirical scaling laws show the dependence i.e., $\tau_E \propto 1/\sqrt{P}$, where $\tau_E$ and $P$ are the energy confinement time and auxiliary heating power, respectively (Kaye and Goldston 1985; Sudo et al. 1990). The discovery of H-mode stimulated searching other favorable operational regimes (Wagner and Stroth 1993; Burrell 1997; Fujita 2002), and really found various kinds of improved confinement modes (ICMs) classified three categories; a family of edge transport barrier (ETB) like VH-mode in DIII-D (Jackson et al. 1991), ones with internal transport barriers (ITB) (Ida and Fujita 2018; Hugon 1992; Koide et al. 1994; Levinton et al. 1995; Strait et al. 1995), and ones without a transport barrier, such as supershot (Strachan 1987) and radiative improved (RI) mode (Messian 1996). On the other hand, similar kinds of ICMs were found in stellarators (Fujisawa 2003; Wagner et al. 2006), ETBs (Erckmann et al. 1993; Toi et al. 1993). ITBs (Fujisawa 1999; Stroth 2001; Alejaldre 2001; Ida 2003) and ICMs without a barrier (Morita et al. 1993; Ida 1996, 1999; Brakel 1997). Nowadays, utilizing these ICMs, reactor-relevant operational scenarios have been developed to pursue the compatibility of steady and high performance in various plasma confinement systems; i.e., current hole, in JT-60 (Fujita et al. 2001), I-mode in tokamaks (Whyte et al. 2010; Stroth 2022; Fenstermacher 2022), HDH-mode in W7-AS (McCormick 2002), super dense core (Ohyabu et al. 2006) and ITB with an impurity hole in LHD (Ida et al. 2009). The clarification of ICM formation mechanisms, particularly H-mode, was one of the research subjects that Sanae pursued throughout her research career with Kimitaka.

## 2.2 Theory of H-mode

*Bifurcation theory* Sanae and Kimitaka proposed the first theory to describe LH-transition based on the bifurcation of the radial electric field, $E_r$ (Itoh and Itoh 1988). These theories predicted that changes in the radial electric field could be a cause of the H-mode transition. An equation to describe $E_r$-generation is introduced to explain the theories. The equation is given as (Itoh and Itoh 1996)

$$\varepsilon_\perp(\partial E_\mathrm{r}/\partial t) = -j_\mathrm{r}(E_\mathrm{r}) = -j_\mathrm{Neo} - j_\mathrm{loss} - j_\mathrm{vis} - j_\mathrm{pvis} - j_\mathrm{trs} - j_\mathrm{flc} - \cdots, \tag{1}$$

where $\varepsilon_\perp$ is the dielectric constant of plasma representing the effect of the polarization current (Shaing et al. 1992). The radial current on the right-hand side is composed of a number of elements: $j_\mathrm{Neo}$, $j_\mathrm{loss}$, $j_\mathrm{vis}$, $j_\mathrm{pvis}$, $j_\mathrm{trs}$ and $j_\mathrm{flc}$ are the currents driven by neoclassical bipolarity (Kovrizhnykh 1984; Hastings 1984), orbit loss (Itoh et al. 1989, 1991; Sanuki et al. 1993), viscosity (Rozhanski and Tendler 1992), parallel viscosity, turbulence Reynolds stress (Diamond and Kim 1991) and fluctuations (Solomon and Shats 2001), respectively. Some of these current elements show nonlinear characteristics to cause $E_r$-bifurcation. In their theory, the two terms are considered to be dominants on the right-hand-side, i.e., anomalous and ion-orbit loss term. If one solves the equation $j_{flc}(E_\mathrm{r}) + j_{loss}(E_\mathrm{r}) = 0$, three solutions, as is shown in Fig. 1, can be found to correspond to bifurcated branches of an unstable, L and H modes. The theory was followed by an analogous one proposed by Prof. K. C. Shaing independently (Shaing and Crume 1989). Although the model was based on poloidal flow dynamics, radial electric field is coupled with poloidal flow through radial force balance, thus, the poloidal flows can be regarded as being equivalent

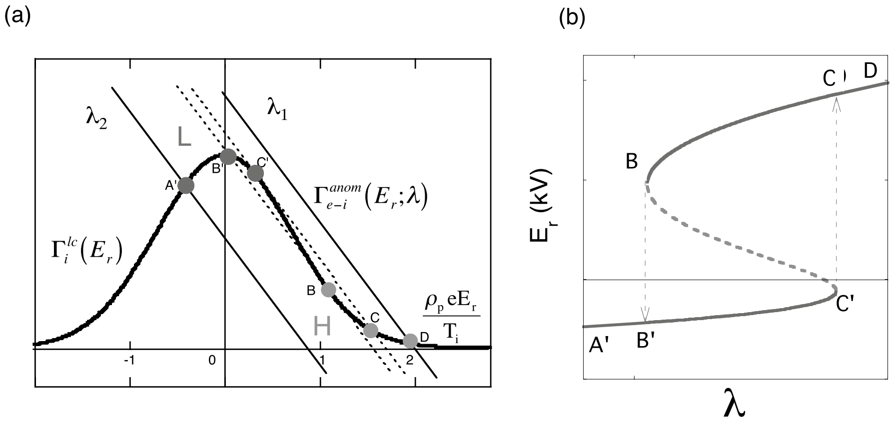

**Fig. 1** A theory for H-mode transition based on bifurcation of radial electric field. The theory assumes that the ion orbit loss current is balanced with anomalous electron current. **a** Ion and electron currents. The Gaussian-like curve and the lines represent the ion orbit loss and anomalous (or fluctuation-driven) current, respectively. **b** Obtained solutions of radial electric field as a function of a variable determining anomalous electron flux. The H-mode solution corresponds to lower balanced flux in the left graph (**a**), and the stronger electric field branch in the right graph (**b**)

to the radial electric field. In case of the Shaing's theory, the combination of the ion-orbit loss and the parallel viscosity term gives similar solutions. While these theories revealed stimulating and contributed to the development of other models, such as one based on Stringer's spin-up (Hassam et al. 1991) and the predator-prey model (Diamond et al. 1994), radial electric field became a long-standing topic in the research of magnetic confinement fusion.

*Self-sustained turbulence* The next challenge to explain the H-mode formation was why the turbulence transport was reduced after the transition of $E_r$-structure. Essential theories are needed to explain experimental observation of turbulence and transport (Liewer 1985; Wootton et al. 1990) and their reductions at a barrier including H-mode (Connor and Wilson 2000). Turbulence should be saturated to satisfy the balance between its growth and decorrelation (or damping) rate, as $\mathrm{d}I/\mathrm{d}t = \gamma_L I - D\Delta I$, where $I$ is the turbulence intensity and the second term represents the damping due to diffusion whose constant is expressed by $D$. Setting $\Delta = k_\perp^2$ in a steady state, the above equation gives the well-known Kadomtsev's expression of the diffusion coefficient, $D = D_0 = \gamma_L / k_\perp^2$. Under the presence of $E_r$-shear (or velocity shear), the turbulence structure is deformed along the direction of velocity, which is characterized by a change of effective perpendicular wavenumber, $k_{\perp,\mathrm{eff}}^2 = k_\perp^2(1 + \omega_{E\times B}^2 \tau_{\mathrm{cor}}^2) \simeq k_\perp^2(1 + \omega_{E\times B}^2/\gamma_L^2)$, assuming that the perpendicular velocity varies as obeying $V_\perp = \omega_{E\times B} x = (E_r/B)' x$, where $x$ is the perpendicular coordinate (Itoh et al. 1994a). Then, the turbulence diffusion coefficient is obtained, as

$$D = \frac{\gamma_L}{k_\perp^2} \frac{1}{(1 + \omega_{E\times B}^2 \gamma_L^{-2})} = \frac{D_0}{(1 + \omega_{E\times B}^2 \gamma_L^{-2})}. \tag{2}$$

The consideration is a guidance for similar expressions that most of theories expect for turbulence reduction due to $E_r$-shear (Itoh et al. 1994a; Shaing et al. 1988; Biglari et al. 1990). Similarly, thermal coefficient should obey the formula like $\chi \sim \chi_0/(1+\alpha_E^2(E_r')^2)$, where $\chi$ and $\alpha_E$ are the thermal diffusivity of the L-mode and a numerical coefficient, respectively. At present this phenomenon is well known as $E_r$-shearing effect that should regulate or suppress turbulence.

Sanae and Kimitaka advanced their thoughts on nonlinear growth of instabilities, and gave a birth to a concept of *self-sustained turbulence*. A mode can be destabilized through nonlinear interactions among fluctuations even if the mode is linearly stable. Thus, the linear growth rate $\gamma_L$ needs to be replaced with nonlinear growth rate $\gamma_{NL}$ in the above expression of diffusivity. Moreover, the nonlinear growth rate of a mode could be balanced with that of nonlinear damping in a stationary state. This leads to the concept that turbulence is self-sustained above a threshold in fluctuation amplitude (Itoh et al. 1992a, b, c), and that such a mode can grow abruptly with a property of subcritical onset. Actually, examples have been found that feature such nonlinear growth of instabilities in simulations (Scott 1990, 1992; Carreras et al. 1992; Dimits et al. 2000). The concept was first applied on interchange mode turbulence (Itoh et al. 1994a; Yagi et al. 1994, 1995). Later, the theory was extended to the ballooning mode turbulence including both L and H modes (Itoh et al. 1994b). For the case of ballooning mode turbulence, the expression of thermal diffusivity is obtained as follows (Itoh et al. 1994b; Yagi et al. 1993; Fukuyama et al. 1994):

$$\chi \sim \frac{1}{1+h_1\omega_{E1}^2+h_2\omega_{E2}^2}\frac{\alpha^{3/2}}{f(s,\alpha)}\left(\frac{c}{\omega_p}\right)^2\frac{v_A}{qR} \tag{3}$$

where $\alpha(=-q^2R\beta')$, $h_1$, $h_2$ and $f$ are numerical coefficients, and $\omega_{E1}$ and $\omega_{E2}$ represent the variables related to electric field shear and electric field curvature, with $\omega_p$, $v_A$, $c$, $q$, $s$ and $R$ being the plasma frequency, the Alfven velocity, the light velocity, the safety factor, the magnetic shear parameter and the major radius of plasma, respectively. The formula demonstrates the importance of $E_r$-curvature in addition to $E_r$-shear, as is shown in Sect. 2.4.

*Predator–Prey model* The nonlinear coupling of fluctuations can generate plasma flows, or radial electric field in toroidal systems, through a phenomenon known as inverse cascade (Hasegawa 1985). In other words, radial currents are induced through the turbulent Reynolds stress and result in the formation of the radial electric field. The turbulence Reynolds stress to generate poloidal flows has been paid attention as an important player in barrier formation, supported by experimental observation (Hidalgo et al. 1999). Taking into account the feedback effect of the generated $E_r$-shear on turbulence (Diamond and Kim 1991; Hidalgo et al. 1999), the interplay between fluctuations and radial electric field is recognized as a mechanism for barrier formation and structural bifurcation in toroidal plasmas (Diamond et al. 1994). Based on the above-mentioned concept, a model termed predator–prey model was proposed to explain the H mode transition. In the model, the interplay between turbulence and its generated flows is expressed as the following simultaneous equations,

$$\begin{aligned} \frac{1}{2}\frac{\mathrm{d}F}{\mathrm{d}t} &= \gamma_0 F - \alpha_1 F^2 - \alpha_2 UF, \\ \frac{1}{2}\frac{\mathrm{d}U}{\mathrm{d}t} &= -\mu U + \alpha_3 UF, \end{aligned} \tag{4}$$

where $F(=(\tilde{n}/n)^2)$ and $U = (V_E')^2$ are the normalized turbulence and the shear flow intensities, respectively. The steady state solutions of the above equations, i.e., $\mathrm{d}F/\mathrm{d}t = \mathrm{d}U/\mathrm{d}t = 0$, correspond to L- and H-mode; that is, $U = 0$, $F = \gamma_0/\alpha_1$ (L-mode) and $U = (\gamma_0 - \alpha_1\mu/\alpha_3)/\alpha_2$, $F = \mu/\alpha_3$ (H-mode). In addition to two stable solutions corresponding to the bifurcated states, the equations also predict limit cycle oscillations as is the Lotka–Volterra equations. Experimental support was obtained (Xu et al. 2000), and more recent simulation with realistic configurations shows that the H-mode transition should occur as synergy of the Reynolds stress and ion-orbit loss effects (Chang 2017).

### 2.3 Experimental confirmation

*Electric field bifurcation* In response to the bifurcation model, the structural change of radial electric field before and after LH-transition was measured with spectroscopic measurements in DIII-D and JFT-2M tokamaks (Ida et al. 1990; Groebner et al. 1990). Figure 2 shows the measurement of $E_r$-profiles in JFT-2M tokamak. The force balance equation, $E_\mathrm{r} = v_\phi B_\theta - v_\theta B_\phi + (\partial p_\mathrm{i}/\partial r)/Zen_\mathrm{i}$, allows to evaluate radial electric field from flow velocities and impurity temperature measured with spectroscopy (Fonck 1984), where $v_\theta$, $v_\phi$, $Z$, $n_\mathrm{i}$, and $\partial p/\partial r$, represent poloidal, toroidal velocities, ion charge, ion density, and ion pressure gradient, respectively. The experiments were performed, soon after the proposal of $E_r$ -bifurcation model, to confirm if the radial electric field really controlled plasma confinement or created transport barrier. In continuous current tokamak (CCT),

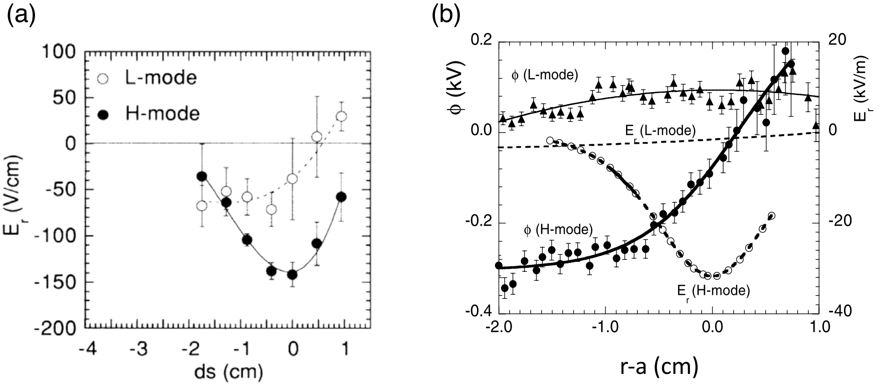

**Fig. 2** Measurement of radial electric field in L- and H-mode in JFT-2M, which shows the clear difference of radial electric field profiles. **a** Radial electric field measured with charge exchange spectroscopy using force balance equation (Ida et al. 1990), and **b** that measured with a heavy ion beam probe (Ido et al. 2000)

TUMAN 3 and TEXTOR tokamak, the hypothesis was experimentally confirmed using a bias electrode inserted to the plasma edge. As a result of employing the biasing electrode, plasmas were successfully forced to make a transition to a better confinement mode (Taylor et al. 1989; Askinazi et al. 1992; Weynants et al. 1992). The $E_r$-structure generated with the bias electrode was discussed theoretically (Rozhansky and Tendler 1992; Stringer 1993; Itoh et al. 1998). The result demonstrates that the change in $E_r$-structure should be the cause of confinement improvement, although there may be a possibility that the mechanism can be different from the case of spontaneous transition.

*Causality problem* The force balance equation raised a causality problem since it showed negative pressure gradient should result in negative radial electric field. Thus, one can consider that the change in radial electric field after H-mode transition can be a result of the barrier formation. The time scale of electric field change was the key to answer the question. The time scale of spontaneous $E_r$-transition was first observed with HIBP in CHS plasma (Fujisawa 1997; Fujisawa et al. 2000) to show that the observed time scale, a few dozen microseconds, was much faster than the confinement time of the plasma, and the change of radial electric field after the transition is positive direction, which may lessen the pressure gradient in the force balance equation. Later in a sawtooth-triggered H-mode transition in JFT-2M, it was also shown that the $E_r$-transition could occur in a few dozens of microseconds, much faster, compared to confinement time scale, in the JFT-2M tokamak (Miura et al. 2001; Ido et al. 2000; Ido 2001). These facts strongly support the hypothesis that the $E_r$-shear should trigger the barrier formation. The barrier formation in CHS is found to completely obey the $E_r$-bifurcation scenario that Sanae and Kimitaka predicted (Itoh and Itoh 1988; Fujisawa et al. 2000; Fujisawa 2021).

*Turbulence reduction* The conditions for turbulence reduction have been tested using the expression of Eq. (2) at a barrier. The formula shows that the fluctuation reduction is effective when $\gamma_L \sim \omega_{ExB}$. Simulations and experiments demonstrated the validity of the condition, $\gamma_L < \omega_{ExB}$, for $E_r$-shear reduction (Waltz et al. 1994; Hahm and Burrell 1995; Waltz et al. 1997); for reviews (Burrell 1997a, b). Moreover, intensive efforts have been made to observe $E_r$-structure and turbulence. Progress in diagnostic techniques for high temperature plasmas (Bretz 1997), such as HIBP (Jobes and Hickok 1970; Schoch et al. 1988; Crowley 1994; Fujisawa et al. 1996), spectroscopy using a diagnostic beam (Fonck 1984; Levinton et al. 1989; Fonck et al. 1993), phase contrast imaging (PCI) (Coda and Porkolab 1995), and reflectometry (Manso 1993; Mazzucato and Nazikian 1993; Mazzucato 1998; Hirsch et al. 2001), has made it possible to measure both fluctuations and radial electric field when transport reduction or transport barrier formation occurs. Experiments using advanced diagnostics have been carried out in DIII-D and W7-AS, reporting that the reduction of local fluctuations is accompanied with $E_r$-shear formation around the ETBs (Doyle et al. 1991; Moyer 1995; Kislov and T-10 Team 2001; Burrel 2001; Wagner 1994). In the enhanced reversed shear (ERS) mode of the TFTR, reflectometry showed drastic suppression of fluctuations of rather long-wavelength inside the barrier (Mazzucato and Nazikian 1993). Moreover, a micro-wave-scattering system found that short wavelength fluctuations of electron skin-depth ($c/\omega_{pe} \sim 1$ mm) was suppressed, and that its temporal behavior was well correlated with the electron transport (Wong et al. 1997). Furthermore, development of diagnostics, such as gas-puff imaging technique, revealed successfully how turbulent eddies should be broken into small pieces in the bias-electrode experiments (Shesterikov et al. 2013).

### 2.4 Contemporary issues for improved confinement

*Edge localized modes and intermediate states* The physics of edge localized modes (ELMs) is a critical issue at present, because their control is extremely important for fusion application in two aspects; to remove confined impurities and ashes from the plasma, and to avoid damage to the surrounding wall due to the energy pulses associated with ELMs. In the early phase of their discoveries, Sanae and Kimitaka regarded the ELMs as repetitive transitions between bifurcates states. According to the concept, they first proposed a model of dithering ELMs, which occurs near the power threshold to H-mode transition, as the repetitive transitions between L- and H-mode (Itoh et al. 1991). Then the model was extended to describe type-I ELMs as repetitive transitions between M-, L- and H-mode; M-mode was introduced as the bifurcated state characterized by braided magnetic field in high-$\beta$ plasma (Itoh et al. 1996). The experiment confirmed that the model should well describe dithering ELMs (Zohm 1994). On the other hand, self-excited or limit cycle oscillations (LCO) were observed in stellarators (Stroth 2001; Fujisawa 1998; Maassberg et al. 2000), Particularly, CHS experiments reported the presence of many bifurcated states in potential with various transition patterns between them, called electric pulsation (Fujisawa et al. 2000). Later, in tokamaks, the finding of an intermediate regime (IM-mode) between L and H mode, characterized by periodic bursts (Colchin et al. 2002), extended the predator and prey model to explain the phenomena (Kim and Diamond 2003). Moreover, later in 2010s, the further findings of I-phase, LCOs between two states dominated by GAM and turbulence (Conway et al. 2011), simulated exploring transient phase between L- and H-mode. Many experiments followed to report similar transient behavior or intermediate states before the full H-mode transition (Estrada et al. 2010; Xu et al. 2011; Schmitz et al. 2012; Estrada et al. 2011; Cheng et al. 2013; Kobayashi et al. 2013; Yan et al. 2014), providing active research field of H-mode formation mechanisms and scenarios involving physics of zonal flows (Cziegler et al. 2014; Czieler et al. 2015; Schmitz 2017).

*Shock structure* The importance of two-dimensional flow structure or poloidal asymmetry in electric field for H-mode transition was pointed out (Shaing et al. 1992; Kasuya and Itoh 2005). As is shown in Fig. 3a, where a shock structure with poloidal asymmetry is expected to be induced during H-mode transition. The asymmetric potential on magnetic field surfaces produces inward convective flows that give a large impact on particle transport and a rapid rise of density inside. A mysterious phenomenon to suggest shock formation was really observed during electric pulsation in CHS, in which repetitive transitions occurs to form steady state oscillation. During the electric pulsation, abrupt density rises at the plasma edge were

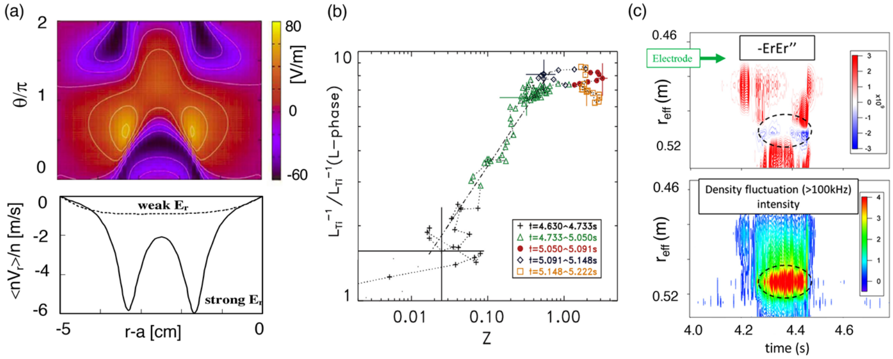

**Fig. 3** **a** Top and bottom panels show poloidal shock structure and induced inward particle flux, predicted in a simulation. The particle fluxes induced by asymmetric electric field structure (or convective fluxes) can explain rapid increase in density observed during H-mode transition (Kasuya and Itoh 2005). **b** The relation between density gradient scale and $E_r$-structure parameter, $Z = (E_r')^2 - E_rE''$, where $E''$ represents the $E_r$-curvature. The density gradient becomes larger as the parameter $Z$ increases (JT60U) (Kamiya et al. 2017). **c** Temporal behavior of turbulence and the $E_r$-curvature in LHD. The top and bottom panels show temporal evolution of the $E_r$-curvature and density fluctuations. It is clear that the turbulence amplitude increases when $E_r$-curvature is expected to enhance turbulence (Tokuzawa et al. 2014)

found to occur simultaneously with drops in potential at the plasma center. The time scales of the rises and drops are in a dozen microseconds, which is much faster than a diffusive one of millisecond (Fujisawa et al. 2000). Two-dimensional observation should be needed to investigate transient heat and particle fluxes in such phenomena as well as rapid electric field change. Particularly, such two dimensional measurement should be of significant importance also for considering dangerously large heat (and particle) fluxes accompanied with ELM crashes.

*Curvature effects of radial electric field* While the magnetic field structure is one of the most important ingredients for improved confinement (Shafer et al. 2004; Waltz et al. 2006), more detailed investigation showed that the strongest reduction of turbulence could occur at the position of minimum radial electric field where $E_r$-shear is rather small (Kamiya et al. 2017). The observation indicated that only $E_r$-shear should not be sufficient to explain turbulence reduction in barrier regions. Then, an important role of $E_r$-curvature was revisited (Itoh et al. 1992a, b, c) to be another ingredient for barrier formation theoretically (Itoh and Itoh 2016). Sanae and Kimitaka introduced a term for a saturation mechanism, which represented nonlinear energy transfer from turbulence to larger scale structure like zonal flows through modulational couplings. Then the equation for turbulence saturation is written as

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \left[\gamma_{NL} - k_\perp^2 D(1 + \alpha Z)\right] I, \tag{5}$$

where $E_r$-structure parameter, $Z = (E_r')^2 - E_rE''$, with $E''$ representing the $E_r$-curvature. In equilibrium, the above equation gives a modified formula of Eq. (2), $D = D_0/(1 + \alpha Z)$. Then the relation between transport and the parameter, $Z$, has been investigated and the hypothesis was confirmed experimentally. Figure 3b, c show examples in JT-60U and LHD that gradient at barrier positions should linearly increase to be saturated with the parameter, $Z$, and that temporal behavior of turbulence amplitude should be correlated with the $E_r$-curvature. The observations demonstrate significant impact of $E_r$-curvature on turbulence reduction (Kamiya et al. 2016; Tokuzawa et al. 2014; Tokuzawa 2017).

# 3 Achievements in Itoh project

## 3.1 Establishment of research center for plasma turbulence

It was 2004 that Sanae started her own project for implementing her integrated research of plasma turbulence in her original manner that unified theory, simulation and experiment. The project was supported by two large grants of Japanese Society for the Promotion of Science (JSPS) (KAKENHI in Japanese) that she acquired sequentially. The project was initiated by the first grant entitled ‘Research on Structural Formation and Selection Rules in Turbulent Plasmas’ from Japanese fiscal year 2004 to 2008, then it was extended by the second one ‘Integrated Research on Dynamic Response and Transport in Turbulent Plasmas’ from 2009 to 2013. Two notable enterprises were undertaken for the period. One is the creation of ‘Kyushu University Itoh Project Prize’ in 2005 in collaboration with Institute of Physics Publishing and Division of Plasma Physics of European Physics Society, which aimed at finding promising young scientists in her/his early career. The other one is the founding of her own research center, named ‘Research Center for Plasma Turbulence’ in 2009. Many worldwide collaborators, including Profs. R. Balescu, G. Bonhomme, R. Dendy, P. Diamond, O. Grulke, K. Hallaschek, T. Klinger, H. Kamitsubo, T. Ohkawa, R. D. Sagdeev, U. Stroth, H. Toki, M. Q. Tran, G. Tynan, F. Wagner, joined the project. Thanks to the project, she promoted domestic and international collaborations in addition to pushing her own works forward. Besides, Sanae had an opportunity to construct her own low temperature facility, and succeeded in obtaining a number of significant results on fundamental processes of turbulent plasmas. This section introduces the achievements mainly on zonal flow physics obtained in experiments strongly supported in Itoh project: CHS, JFT-2M and her own facility.

## 3.2 Physics of zonal flows

*Zonal flow identification* Sanae and Kimitaka were among the pioneers of the study of zonal flows in plasma physics (Itoh et al. 2006). In 1996, a simulation result based on gyrofluid model sensationally called into question whether ITER could reach ignition (Glanz 1996). A theoretical answer was that turbulence driven flows should not be strongly damped in collisionless processes (Landau damping), and that the undamped flows, called zonal flows, should play a significant role in turbulence saturation (Rosenbluth and Hinton 1998). The situation stimulated simulations and experiments on zonal flows (Fujisawa 2009; Tynan et al. 2009; Garbet 2010).

Simulation works demonstrated that short-wavelength turbulence could generate zonal flows (Hasagawa and Wakatani 1987; Lin et al. 1998) through nonlinear couplings, and that the zonal flows could regulate the short-wavelength turbulence again to control transport (Hahm et al. 1999). Then, many experimental trials were carried out to search for zonal flows (Fujisawa et al. 2004; Xu et al. 2003; Gupta et al. 2005), while Sanae published the well-known review for the physics of zonal flows with Prof. P. H. Diamond and colleagues (Diamond et al. 2005).

The zonal flows are fluctuating mesoscale structures, which are driven by microscale instabilities such as drift waves. The zonal flows are symmetric around the magnetic axis, and have no poloidal wave number with a finite radial one in mesoscale. During the period, the identification of zonal flows was completed with twin HIBPs in CHS plasma (Fujisawa et al. 2004). Figure 4 shows the spectrum of the measured electric field fluctuations. In the measurements, it was confirmed that the low frequency fluctuations less than $\sim 1$ kHz showed a long-distance correlation. This is one of the characteristics for zonal flows to satisfy. The correlation analysis deduced a spatiotemporal structure of the low-frequency electric field fluctuations; note that Sanae called this method ’Correlation Hunting’. The result shows that it should have a sinusoidal structure of a finite radial wavelength of $\sim 1.5$ cm in mesoscale, and that the structure should decay in timescale of $\sim 1.5$ ms. In the same experiments, zonal magnetic fields (Diamond et al. 2005; Gruzinov et al. 2002; Guzdar et al. 2001) were found to coexist with zonal flows with extended use of the HIBP (Fujisawa et al. 2007). The result demonstrates that turbulence has an ability to generate magnetic fields in mesoscale.

*Geodesic acoustic modes* Geodesic acoustic modes (GAM) form one of the physics issues that attracted the interests of Sanae and Kimitaka. The GAMs are oscillatory branches of zonal flows that can only emerge in toroidal plasmas. The oscillatory property makes it easier to detect GAMs than stationary zonal flows, thus, a huge number of experimental works have been reported, as is explicitly shown in a recent exhaustive review (Conway et al. 2022), both in tokamaks and stellarators (Nagashima et al. 2005; Shats 2002; Jakubowski et al. 2009; Nagashima 2006; Zhao

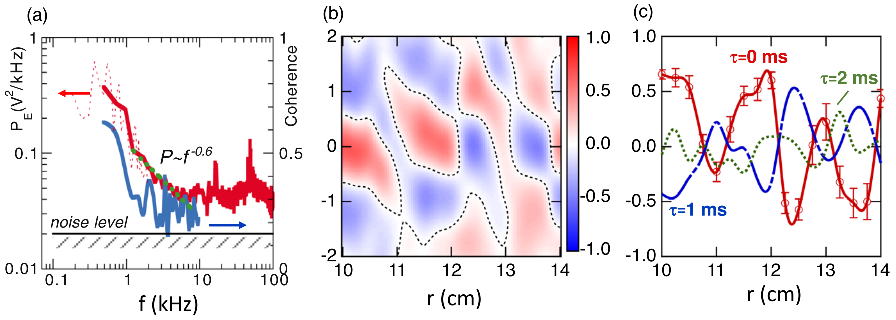

**Fig. 4** Identification of zonal flows in CHS (Fujisawa et al. 2004). **a** Spectra of electric field fluctuations. **b** Spatiotemporal correlation functions of electric field between two toroidal positions. The dashed line shows the position where the correlation value is zero. **c** The spatial correlation functions at $\tau = 0$, 1, and 2 ms. The shapes of the deduced correlation function correspond to the structures of zonal flows

et al. 2006; Schoch 2003; Hamada 2005; Ido 2006; Melnikov 2006; Mckee 2003; Krämer-Flecken et al. 2006; Fujisawa et al. 2007). These inter-experimental comparisons confirmed the essential characteristics of GAM frequencies, $f_{\mathrm{GAM}} \propto c_s/R$, where $c_s$ is sound speed, the spatial symmetry ($m = n = 0$) in potential fluctuations, and $m = 1$ nature in density fluctuations (Zhao et al. 2006). On the other hand, experimental observations often reported the eigenmode characteristics of GAM; the frequency appeared constant over a certain radial extent of the identical GAM profile that exhibits discrete and intermittent changes, regardless of radial variation of electron temperature to give dependence of local GAM frequency. After paying attentions on the eigenmode characteristics (Itoh et al. 2006), Sanae and Kimitaka devised a novel method, called GAM spectroscopy, that determines the effective ion mass through the ion sound velocity (Itoh et al. 2007) in addition to the exact position of plasma boundary (Nagashima 2009; Itoh 2016). The GAM spectroscopy was further extended to infer the safety factor under co-existence of ion acoustic mode (Itoh et al. 2009). The possibility of ion mass detection for evaluating fuel ratio in fusion plasmas, and the other essential plasma parameters could be beneficial in future burning plasmas. In addition to the above works, they led many of experimental, theoretical and simulation works on GAMs, including their basic excitation mechanisms (Itoh et al. 2005; Sasaki 2009), turbulence enhancement and suppression due to its trapping of GAM structure (Sasaki 2017; Sasaki et al. 2018), experimental confirmation of the turbulent Reynolds stress drive of GAMs (Kobayashi 2018), and the mechanism of energetic particle excited GAMs (E-GAMs) that should work as transfer channels of momentum and energy to bulk ions (Sasaki et al. 2011; Sasaki 2017),

*Zonal flow effects on turbulence and transport* Zonal flows affect turbulence and confinement through effects of their turbulence shearing, their quasi-energy conservation with turbulence (or energy partition), and turbulence trapping (Kaw 2002) that can contribute to turbulence spreading (Mattor and Diamond 1994; Garbet et al. 1994; Hahm et al. 2004; Kobayashi 2022). Zonal flow shearing was confirmed in several experiments of smaller plasma experiments in the early phase of the research, for example, H1 heliac (Shats et al. 2003) and TJ-K (Birkenmeier et al. 2013; Ullman et al. 2020). The effects of energy partition was demonstrated in transport barrier formation of CHS. After transport barrier is formed, the increase in electron temperature inside the barrier was observed as a puzzling fact, since the inside $E_r$-shear was not large enough to reduce the turbulence. Detailed investigation of energy partition showed that the energy of zonal flows should increase after the barrier formation, hence the turbulence was reduced consequently to improve confinement without $E_r$-shear inside. Note that the cause of the increase of zonal flow fraction is ascribed to the reduction of neoclassical viscosity (Fujisawa et al. 2008). The result clearly demonstrates the importance of the energy partition for confinement (Itoh 2007; Toda et al. 2007). The direct interaction between zonal flows and turbulence, probably turbulence trapping, was also observed in CHS (van Milligen et al. 1995; Fujisawa 2006). As is shown in Fig. 5a, increase (or decrease) in turbulence amplitude is synchronized with decrease (or increase) in zonal flow's amplitude. Moreover, the nonlinear couplings between elemental waves in turbulence should be stronger at minima of zonal flows (Fujisawa et al. 2007a, b). A simulation

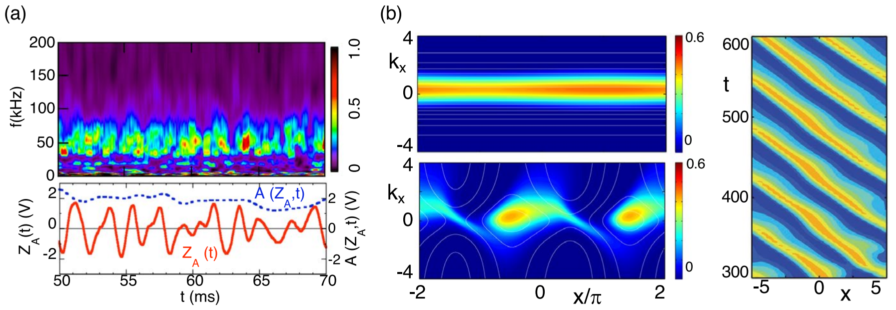

**Fig. 5** Turbulence trapping and spreading due to zonal flows. **a** Experimental results to suggest turbulence trapping due to stationary zonal flows (Fujisawa et al. 2007a). **b** Simulation results of turbulence spreading caused by GAM trapping. The left panels show the wave number distribution as a function of radius at the initial and turbulence saturated state, while the right panel does the turbulence propagation in the radius/time domain (Sasaki et al. 2018). It is clearly shown that the trapped turbulence is transferred inward

work also showed turbulence trapping of GAMs. Figure 5b shows the simulation results to demonstrate that GAMs could trap turbulence in their valley and convey the turbulence along their trajectories of propagation and could result in turbulence spreading that enhanced transport in a turbulence-free region (Sasaki 2017).

*Anatomy of turbulence and findings* Sanae and Kimitaka were ambitious in developing advanced methods to analyze turbulence, or visualize turbulence interaction, which they call *anatomy of turbulence* (Itoh et al. 2005, 2017). Following early works (Moyer et al. 2001; Tynan et al. 2001), the nonlinear

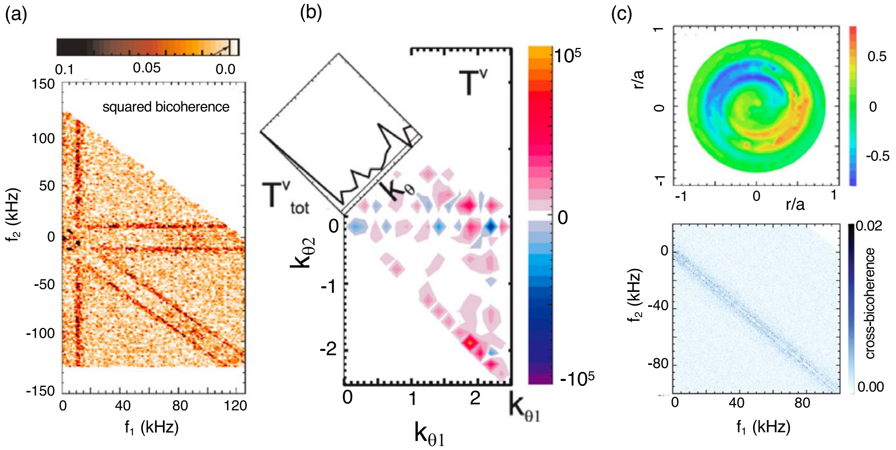

**Fig. 6** Analyses of nonlinear couplings. **a** Bicoherence analysis on frequency domain to prove that GAM is generated by nonlinear couplings with background turbulence in JFT-2M (Nagashima et al. 2005). **b** Energy transfer analysis on wavenumber domain to prove that stationary zonal flows are generated by nonlinear couplings with background turbulence in TJ-K (Manz et al. 2009b). **c** The top and bottom panels show a reconstructed image of the giant fluctuating structure, and the result of bicoherence analysis to prove that a giant fluctuating structure is generated with background turbulence in LHD, respectively (Inagaki et al. 2011)

couplings between GAMs and background turbulence was confirmed, as is shown in Fig. 6a, using bicoherence analysis on a reciprocating Langmuir probe data in ohmically heated plasma of JFT-2M (Nagashima et al. 2005). The analysis also succeeded in evaluating coherent biphase, i.e,, phase relationship between GAM and turbulence modulation (Nagashima 2006). Before the bicoherence analysis was widely provided, the power transfer function (PTF) analysis was invented to elucidate not only the presence of nonlinear couplings but energy transfer direction between different scale fluctuations or structures in plasma turbulence (Ritz et al. 1989; Kim et al. 1996, 1997; Xia and Shats 2003; Nagashima et al. 2008). The analysis method, based on Hasegawa–Mima equation (Hasegawa and Mima 1977) evaluates the power transfer function $T(k_1, k_2)$ using the following formula, $\partial P_k/\partial t = 2\gamma_k P_k + \sum T(k_1, k_2)$, where $\gamma_k$ and $P_k$ represent linear growth rate and the power of a mode. After the first PFT analysis on frequency domain (Ritz et al. 1989; Xu et al. 2010), it was applied on wavenumber domain using two dimensional (2D) probe data (Manz et al. 2008, 2009a). In TJ-K torsatron, the energy transfer was evaluated the two-dimensional wavenumber space, and finally as is shown in Fig. 6b, succeeded in proving the nonlocal energy transfer from drift-waves to zonal flows (Manz et al. 2009b). On the other hand, the integrated analysis of correlation hunting and visualizing nonlinear processes in Itoh project allowed a discovery of a giant fluctuating structure in LHD (Inagaki et al. 2011). The structure fluctuates over the plasma cross-section, as is shown in Fig. 6c with a frequency in a few kHz range. The structure is considered to be a nonlinearly excited metastable mode, probably ones related to dissipative trapped ion modes (DTIM) (Kadomtsev and Pogutse 1971), by the background turbulence; the nonlinear couplings were confirmed using the cross-bicoherence analysis in Fig. 6c. The experimental result demonstrates that turbulence can generate a macroscopic structure as well as mesoscale ones like zonal flows.

### 3.3 Construction of low temperature facility and its physics achievements

*Promotion of cylindrical plasmas* Low temperature plasma experiments, whether linear or toroidal in geometry, can provide a suitable arena for studying the physics of plasma turbulence. The advantageous points of such experimental facilities are as follows; (i) high accessibility, superior flexibility, quick turn-around of experiments, (ii) excellent controllability of plasma, (iii) easy acquisition of a huge amount of data for statistics, and (iv) suitability to use traditional probes and to develop new advanced diagnostics. In Itoh project, a linear plasma system named large magnetic device (LMD) (Shinohara et al. 2009) was upgraded to LMD-U, and later was fully modified to a plasma system, named Plasma assembly for nonlinear turbulence analysis (PANTA), for plasma turbulence research. The physics target of the experiment is to investigate fundamental processes of plasma turbulence mainly using multi-channel probe arrays (Oldenbürger et al. 2012; Yamada et al. 2007; Nagashima et al. 2011). The system has produced versatile results in plasma physics as well as contributions to advanced diagnostics and turbulence analyzing techniques (Kobayashi et al. 2010, 2011, 2012, 2021). The physics achievements include identification of fundamental processes and properties of turbulence (Nagashima et al. 2009, 2011; Ohyama et al. 2012), findings of solitary wave oscillations (Arakawa et al. 2009, 2010, 2011) and streamers (Yamada et al. 2008, 2010; Kin et al. 2018; Yamada et al. 2018; Kin et al. 2019), visuallization of interaction between nonlinear structures (Arakawas et al. 2016), remote energy transfer between local turbulence through zonal flows (Nagashima et al. 2011), difference in local and global-averaged transport fluxes (Nagashima et al. 2011), while development of fundamental tools does bispectral analyses (Kobayashi et al. 2010, 2011, 2012) and tomography (Fujisawa et al. 2015, 2016; Yamasaki et al. 2020; Moon et al. 2021). Three selected topics amongst them are explained below.

*Nonlocal energy transfer* In the earlier phase of the project co-existence of zonal flows and drift waves was confirmed in a plasma parameter region of LMD-U. In the plasma, energy transfer between zonal flows and drift waves was evaluated using the cross-bispectrum described as $\langle E_r(f_{ZF})^* E_r(f_1) E_\theta(f_2)\rangle$, where $\langle\rangle$ represents statistical average. The turbulence Reynolds stress term (or so-called Reynolds force) $\partial_r \tilde{u}_r \tilde{u}_\theta$ to generate zonal flows is expressed as the above cross-bispectrum in the Fourier domain. As is shown in Fig. 7a, the result indicates that the zonal flows should gain the drift wave energy in the plasma interior where a steep density gradient exists, while in the outer region the energy transfer is opposite (Nagashima et al. 2009). The result suggests that the spatial energy transfer should occur through the zonal flows. On the other hand, a similar analysis applied to beam emission spectroscopy (BES) data in DIII-D revealed a role of zonal flows; GAM convection mediated the energy transfer from low (< 40 kHz) to high (> 150 kHz) frequency fluctuations (Holland et al. 2007).

*Identification of streamers* Existence of streamers were identified in LMD-U and PANTA (Yamada et al. 2008; Kin et al. 2018, 2019). They were searched in torus plasma due to their importance on transport, however a few experiments

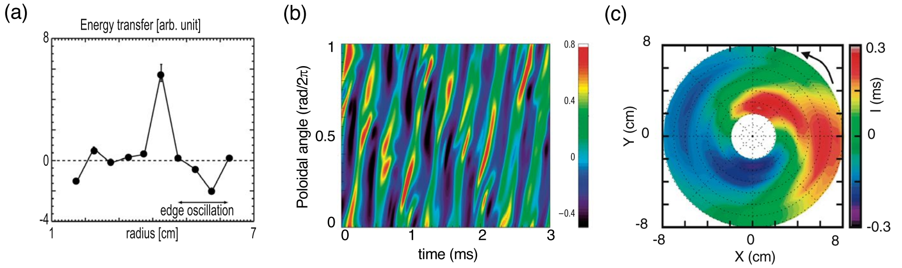

**Fig. 7** Example of fundamental experiments using multichannel probe arrays for plasma turbulence. **a** Energy transfer analysis based on cross-bicoherence that shows non-local energy exchange between zonal flows and local turbulence in LMD-U (Nagashima et al. 2009). **b** Signals of streamers in ion saturation current measured with 64-channel azimuthal probes (Yamada et al. 2008). The 64 channel probes are located at an outer radius of the plasma. The carrier wave (stripes in figure ) propagates in electron diamagnetic direction (positive direction in azimuthal coordinate), while the streamers (spots on stripes) rotate in the opposite (or ion diamagnetic) direction. **c** A reconstructed image of streamers obtained using conditional averaged technique (Kin et al. 2019). The image shows the structure that should be azimuthally localized and radially elongated

reported only signature of the existence (Politzer 2000; Hamada et al. 2006). Some of the phenomena could be ascribed to so-called avalanches caused by a domino-like process as expected in the model of self-organized criticality (SOC) (Bak et al. 1987; Diamond and Hahm 1995; Carreras et al. 1996; Newman et al. 1996; Kosuga et al. 2013; Hahm and Diamond 2018). The streamers are short-lived localized structure, whose shapes are radially elongated and poloidally (or azimuthally) localized, They are expected to be formed from the nonlinear couplings of background turbulence as is similar to zonal flows. However, streamers, differently from zonal flows, enhance the transport (Diamond et al. 2001; Nozaki et al. 1979; Beyer et al. 2000). The anatomy using developed analysis tools confirmed that the streamers are generated through nonlinear couplings between the modes called carriers (drift-waves) and mediator, and that streamers are symmetric along the magnetic axis direction (Yamada et al. 2018). Figure 7b, c shows that their temporal behavior and reconstructed two-dimensional image of streamer (Yamada et al. 2008, 2010). Moreover, later it was confirmed that they really induced ballistic transport to directly connect the plasma core to the edge in one order faster time scale than that of stationary turbulence, and that the envelope of streamers and mediator was found to have the feature of solitons; both become more sharpened as their amplitude increases, demonstrating the characteristics of solitons (Kin et al. 2018). Moreover, it was recently theoretical expected that the nonlinear evolution of streamers should lead to transient excitation of breaths (or Rogue waves in ocean) (Kosuga 2022).

*Strongly correlated turbulence* In a plasma parameter region of PANTA, coexistence of two kinds of instabilities, resistive drift wave and D'Angelo modes (or parallel velocity gradient (PVG) mode) (D'Angelo 1965; Catto 1973; Barbet 1999) was found: the PVG mode has been receiving a lot of attention recently owing to its capability of zonal flow generation due to potential vorticity mixing (Kosuga 2017), and three-dimensional helical flow generation (Kosuga et al. 2020). The two instabilities played a major role of sustaining the plasma structure (Inagaki et al. 2016). These two instabilities induce particle and momentum fluxes through their associated fluctuations (Kosuga et al. 2015; Sasaki et al. 2017). The D'Angelo mode drives the inward directing particle fluxes to sustain the density gradient to cause the drift mode, while the drift mode does momentum fluxes to sustain the velocity shear to cause the D'Angelo mode. Therefore, two different kinds of instabilities sustain each other, that is, one maintains the free energy source or structural inhomogeneity to cause the other. The present case of PANTA provides an example of spatial structure sustained through collaboration of different instabilities that are strongly correlated with each other. Note that a simulation work reproduced repetitive transition between L- and H-mode due to temporal competition between resistive drift wave and Kelvin–Helmholtz instablities (Numata 2007). This observation led Sanae and Kimitaka to acquire a new concept of *strongly correlated turbulence*, and to become aware of the advanced problems how structure and dynamics are selected in a non-equilibrium system where various kinds of inhomogeneity coexist and compete to drive different instabilities.

# 4 Some remaining challenges

## 4.1 Unsolved questions of interest to Sanae

The preceding sections have briefly described Sanae's achievements in H-mode physics and the Itoh project. These are only a subset that can be introduced here among other works with so wide and multifaceted prospects: for instance, the series of statistical theories (Itoh and Itoh 1998, 1999, 2000a, b, c) and exhaustive monographs such as 'Transport and Structural Formation in Plasmas' (Itoh et al. 1999; Yoshizawa et al. 2003; Diamond et al. 2010). This section introduces some of remaining physics problems that Sanae challenged intensively.

*Abruptness and symmetry-breaking in collapse phenomena* Sanae published a review paper entitled 'Physics of collapse events in toroidal plasmas' in 1998. She discussed of structure and dynamics in catastrophic phenomena, such as sawtooth oscillations, ELMs, and disruptions (Itoh et al. 1998). Sanae focused on their probabilistic occurrence and the explosive growth of catastrophic event, and notified that the key to clarify the physics of collapse should be the symmetry-breaking perturbation, which is distinguished from the precursors, to trigger the explosive growth of instabilities. In other words, abrupt structural change could be triggered by a local event to break symmetry of plasma, which could be subcritical nature of instabilities originating from nonlinear interactions between elemental waves and modes in turbulence (Itoh et al. 1998; Dimits et al. 2000).

Recently, several experiments have suggested the important roles of symmetry-breaking phenomena for abrupt changes of global structure. It has been recently found that the onsets of bursty phenomena should happen to begin at a local position; for example, ELMs (Lee et al. 2017), sawtooth instability (Yun et al. 2011), and tongue instabilities in LHD (Ida et al. 2016). The common feature of these phenomena is the occurrence of a local event to trigger the abrupt and global changes of structure. Moreover, the subcritical onset of GAMs was observed, which was caused by phase space distortion (Ido et al. 2016; Lesur et al. 2016; Itoh 2016; Wang et al. 2018). The concept of symmetry breaking should be key to understand the underlying physics of the abrupt changes in the entire plasma structure.

*Nonlocal transport and its hysteresis* Nonlocal transport is a long-standing problem. The famous examples should be the Gentle's cold pulse (Gentle 1995), and the Cordey's core-edge link on H-mode transition (Cordey 1995), while many others are available in both tokamak and stellarator experiments (Luce et al. 1992; Lopes Cardozo 1995; Kissick et al. 1996; Galli et al. 1998; Mantica et al. 1999; Galli et al. 1999; Milligen et al. 2002; Inagaki et al. 2004, 2006a, b; Tamura et al. 2007). The mysterious points of these phenomena are that plasma transport at remote location from a position at which a perturbation is applied start to change in much shorter time scale than the confinement time or diffusive time. A possible candidate to explain the nonlocal transport or *global linkage* should be the nonlinear couplings between disparate scale of fluctuations. Communication between turbulence at two spatial points, even if located away more than the correlation length, is possible through the nonlinear couplings with long correlation structure, such as zonal flows, streamers and giant fluctuating structure.

On the other hand, it is commonly observed, for example, in ECH modulation experiment in LHD (Inagaki 2013), that the local transport can change immediately at the time a perturbation is applied without waiting for changes of local plasma parameters. Sanae and Kimitaka advocated a theory to explain the observations, with a simple phrase to express their theory ‘Heating heats turbulence’. The phrase means that heating itself should cause a dynamics force through the distortion of phase space distribution (Itoh and Itoh 2012) to enhance additional turbulence, according to the formula (Itoh and Itoh 2013)

$$I = \frac{1}{1 - \gamma_h \chi_0^{-1} k_\perp^{-2}} I_0, \tag{6}$$

where $I_0$, $\chi_0$ and $\gamma_h$ represent fluctuation intensity without heating, turbulence heat conductivity and growth rate parameter, respectively. This formula shows that fluctuations should increase (Itoh and Itoh 2012) if $\gamma_h \sim \chi_0 k_\perp^2$; the condition can be satisfied easier in smaller wave numbers. Nonlocal transport, which could be the result of the change in a macroscopic fluctuation structure, should occur with auxiliary heatings. Actually in an ECR-heating modulation experiment in LHD, the rise and drop of turbulence amplitude and resultant flux were really observed to induce transport flux changes, showing a transport hysteresis, simultaneously with increase and decrease in the heating power (Ida 2015).

*Effects of hydrogen isotope and fueling* The hydrogen isotope effect is also a long-standing problem (Bessenrodt-Weberpals et al. 1993; Stroth 1998) giving underlying physics for the operational scenario and modeling for fusion performance strategy (Garcia et al. 2019). The essence of the hydrogen isotope effect is that deuterium plasma shows better confinement than that of hydrogen in contradiction to the prediction of gyro-Bohm dependence. Many experimental trials have been made to clarify the origin of the isotope effect both in tokamak (Xu et al. 2013) and stellarators, including LHD (Yamada et al. 2019; Kobayashi et al. 2019), in addition to theoretical works to investigate isotope effects (Hahm 2013; Itoh and Itoh 2016).

More recently, Sanae and Kimitaka proposed another theory in somewhat analogous concept of heating effects. They expressed the essence of the theory with a simple phrase ‘Fuel feeds turbulence’ (Itoh and Itoh 2012), suggesting the importance of atomic and molecular processes for confinement. The neutrals imprinted by the fluctuations in scrape-off-layer (SOL) penetrate into core plasmas, and enhance the core plasma fluctuations (Itoh et al. 2017). Then heavier ions should have less effect on the core fluctuations. They applied the concept on improved confinement associated with wall conditioning and gas puffing, such as supershot and improved ohmic confinement (Strachan 1987; Soldner 1988; Itoh et al. 1995). It should be mentioned that they derive the following formula, which indicates that density peaking should be restricted by neutral sources (Itoh and Itoh 2019)

$$\frac{\langle n_e \rangle_{vol}}{\langle n_e(a) \rangle} < K\rho_i \frac{\Delta_n \tau_p}{a} \frac{C_s}{L_n}, \tag{7}$$

where $K$, $L_n$, $\Delta_n$, $\tau_p$, $C_s$, $a$ represent the typical wave number of gradient-driven turbulence, gradient scale length, the penetration length of neutral particles, the global particle confinement time the ion sound velocity and the minor radius, respectively. The concepts need future experimental confirmation.

*Advanced diagnostics and phase space structure and dynamics* Sanae and Kimitaka provided several key concepts for further understandings of structural formation and dynamics of turbulent plasmas: bifurcation, global linkage, symmetry-breaking, abruptness, strongly correlated instabilities, effects of heating and fueling including atomic and molecular processes, etc. They also tried to promote experiments and simulations along these concepts. The research along these key concepts could need advanced experiments with new diagnostics that can cover the entire plasma region with locally fine resolution; it may need new plasma experimental system that enables such advanced measurements. A system of tomography, which has been used to detect MHD activities (Nagayama 1988; Park et al. 2006; Nagayama 1987), was developed to examine its feasibility of the measurement for the entire field of plasma turbulence a wide range from micro-scale ( ~ ion Lamor radius) to macro-scale (~ plasma radius) under a project of KAKENHI (specially promoted research) entitled 'Plasma Turbulence Observation System for Puzzling Out the Principles of Structural Formation and Functional Expression in Turbulent Plasmas' from 2017 to 2021. The feasibility for such turbulence measurement was confirmed (Fujisawa et al. 2015, 2016; Yamasaki et al. 2020), and the system has been upgraded to measure three dimensional structure and dynamics of such turbulence field, and to reveal its unique features in PANTA (Moon et al. 2021). Synthetic diagnostics, which she started in Itoh project (Kasuya 2018; Sasaki 2018), have been developed to simulate actual turbulence signals presumed in measurements, and contributes to clarifying its own limitation of diagnostics by evaluating deformation of the measured signals from the real turbulence.

Finally, in contrast to neutral fluids, phase space structure and dynamics should play an important role in structural formation and dynamics of turbulent plasmas (Biglari 1988; Kosuga 2017), as vortex-like structure in phase space, called granulations, was suggested in 1970s (Dupree 1972; Dupress 1970; Kadomtsev and Pogutse 1970). Various kinds of phenomena related to phase space can be expected such as conversion of poloidal flows to toroidal flows (Kosuga 2013), frequency chirping instabilities (Berk 1999), explosive growth of instabilities (Lesur 2017), zonal flow generation (Kosuga and Diamond 2012), and the direct enhancement of turbulence due to auxiliary heatings (Itoh and Itoh 2012). Then the importance of the phase space measurement becomes crutial for further understanding of turbulent plasmas. At present, a new system of charge exchange recombination spectroscopy (CXRS) is being developed to aim at measuring phase space dynamics. Development of advanced diagnostics to access phase space information should be a challenging subject in future to clarify turbulent plasmas under a project of KAKENHI (specially promoted research) entitled *'Research for New Paradigm of Transport due to Phase Space Fluctuations in Fusion Plasma'* from 2021 to 2025.

### 4.2 Concluding remarks

This memorial note shows, by reviewing the achievements of Prof. Sanae-I. Itoh, that she made tremendous contributions to research in plasma physics and nuclear fusion, in experiment and simulation as well as in theory. At present, Wendelstein 7-X stellarator has started operation to aim at compatibility of steady-state operation and better confinement, in other words, to combine the advantages of the stellarator and tokamak confinement systems, in the sense of the symmetry of the magnetic field configurations (Klinger et al. 2019). Regarding the fusion performance, it was good news that the JET tokamak recently achieved doubling the record of fusion production energy (Gibney 2022), while recently the inertial fusion experiment in National Ignition Facility (NIF) demonstrated its great progress and promising future in achieving the fusion product $Q = 0.67$ (Clery 2021), and the latest one $Q \sim 1.5$ (Clery 2022) , where $Q$ is the ratio of fusion product to the input power. Moreover, using artificial intelligence (A.I.) to support the search for improved magnetic configurations has enabled excellent plasma performance in Tokamak à configuration variable (TCV) (Degrave et al. 2022). All these achievements tell us that really a new age has come to fusion research. However, a more precise and accurate prediction of plasma performance, based on physical first principles, is mandatory for efficient and early stage realization of a fusion reactor, particularly for avoiding uneconomical experimental costs for modern and future huge plasma confinement systems. Thus, research into the physics of plasma turbulence should be maintained to obtain solutions of many unsolved problems that Sanae continued to challenge. For obtaining sufficient understandings of plasma turbulence, it is essential to proceed the research under tight collaboration between theory, simulation and experiment. In order to improve the understanding of plasma turbulence to the level required, it is essential that research proceeds with close collaboration between between theory, simulation and experiment. In parallel with fusion-oriented research, specialized experiments in facilities oriented towards the fundamentals of plasma turbulence are called for. (Fujisawa 2021; Fujisawa and Conf 2018; Itoh et al. 2018). Finally, it is worthwhile to mention and her dreams should have been much more ambitious and so passionate; to mention that Sanae promoted an ambitious unified research plan across all fields of plasma physics and technology such as fusion, laser produced and processing plasmas, under the title of 'Research Network on Non-equilibrium and Extreme State Plasmas'. Sanae's phrase, 'Plasma is rich in bifurcation', expresses concisely the attractive nature of plasma as a subject of the modern physics, a system of ultimate states in non-equilibrium.

**Acknowledgements** The paper is dedicated to Prof. Sanae-I. Itoh, in sincere respect for her outstanding efforts and distinguished achievements through her life, particularly in developing important new avenues for the investigation and understanding of plasma turbulence; and with the deepest condolences of the authors to Prof. Kimitaka Itoh, who lost his precious partner in research and private life. The authors would like to express our appreciation to all members of the Research Center for Plasma Turbulence at

Kyushu University, including Drs. H. Arakawa, F. Kin, T. Kobayashi, M. Lesure, C. Moon. S. Nishimura, S. Oldenbürger, S. Sugita, S. Toda, and to all collaborators with Itoh project, including Profs. R. Dendy, P. H. Diamond, A. Fukuyama, O. Grulke, K. Hallaschek, T.S. Hahm, S. Hamaguchi, R. Hatakeyama, K. Ida, T. Ido, A. Iiyoshi, S. Inagaki, J. Q. Dongi, K. Kamiya, Y. Kawai, T. Klinger, R. Kodama, K. Matsuoka, Y. Miura, S. Shinohara, U. Stroth, G. Tynan, F. Wagner, M. Yagi, K. J. Zhao, H. Zushi. The authors thank Prof. R. Dendy for suggestions on the text of a draft of this note. This work was partly supported by JSPS KAKENHI Grant Nos. JP22H00120 and JP17H06089.

## References

C. Alejaldre et al., Nucl. Fusion **41**, 1449 (2001)
H. Arakawa, K. Kamataki, S. Inagaki et al., Plasma Phys. Control. Fusion **51**, 085001 (2009)
H. Arakawa, S. Inagaki, Y. Nagashima et al., Plasma Phys. Control. Fusion **52**, 105009 (2010)
H. Arakawa, T. Kobayashi, S. Inagaki et al., Plasma Phys. Control. Fusion **53**, 115009 (2011)
H. Arakawas, S. Inagaki, M. Sasaki et al., Sci. Rep. **6**, 33371 (2016)
L.G. Askinazi, V.E. Golant, S.V. Lebedev, V.A. Rozhanski, M. Tendler, Nucl. Fusion **32**, 271 (1992)
P. Bak, C. Tang, K. Wiesenfield, Phys. Rev. Lett. **59**, 381 (1987)
X. Barbet et al., Phys. Plasmas **6**, 3953 (1999)
H.L. Berk et al., Phys. Plasmas **6**, 3102 (1999)
M. Bessenrodt-Weberpals, F. Wagner, O. Gehre et al., **33**, 1205 (1993)
P. Beyer, S. Benkadda, X. Barbet, P.H. Diamond, Phys. Rev. Lett. **85**, 4892 (2000)
Biglari et al., Phys. Fluids **31**, 2644 (1988)
H. Biglari, P.H. Diamond, P.W. Terry, Phys. Fluids B **2**, 1 (1990)
G. Birkenmeier, M. Ramisch, B. Schmid, U. Stroth, Phys. Rev. Lett. **110**, 145004 (2013)
R. Brakel et al., Plasma Phys. Control. Fusion **39**, B273 (1997)
B. Bretz, Rev. Sci. Instrum. **68**, 2201 (1997)
K.H. Burrel, Rev. Sci. Intrum. **72**, 906 (2001)
K.H. Burrell et al., Phys. Plasmas **4**, 1499 (1997)
K.H. Burrell et al., Phys. Plasmas **6**, 4418 (1997)
K.H. Burrell, Phys. Plasma **4**, 1499 (1997)
B.A. Carreras, V.E. Lynch, L. Garcia, P.H. Diamond, Phys. Fluids B **5**, 1491 (1992)
B.A. Carreras, D. Newman, V.E. Lynch, P.H. Diamond, Phys. Plasmas **3**, 2903 (1996)
P.J. Catto et al., Phys. Fluids **16**, 1719 (1973)
C.S. Chang et al., Phys. Rev. Lett. **118**, 175001 (2017)
J. Cheng, J.Q. Dong, K. Itoh, L.W. Yan, M. Xu, K.J. Zhao et al., Phys. Rev. Lett. **110**, 265002 (2013)
D. Clery, Science **373**, 841 (2021)
D. Clery, Science **378**, 1154 (2022)
S. Coda, M. Porkolab, Rev. Sci. Instrum. **66**, 454 (1995)
R.J. Colchin, M.J. Schaffer, B.A. Carreras et al., Phys. Rev. Lett. **88**, 255002 (2002)
J.W. Connor, H.R. Wilson, Plasma Phys. Control. Fusion **42**, R1 (2000)
G.D. Conway, C. Angioni, F. Ryter et al., Phys. Rev. Lett. **106**, 065001 (2011)
G.D. Conway, A.I. Smolyakov, T. Ido, Nucl. Fusion **62**, 013001 (2022)
B. Coppi, Plasma Phys. Control. Fusion **5**, 261 (1980)
J.G. Cordey et al., Nucl. Fusion **35**, 505 (1995)
T.P. Crowley, IEEE Trans. Plasma Phys. Sci. **22**, 291 (1994)

I. Cziegler, G.R. Tynan, P.H. Diamond et al., Plasma Phys. Control. Fusion **56**, 075013 (2014)
I. Czieler, G.R. Tynan, P.H. Diamond et al., Nucl. Fusion **55**, 083007 (2015)
D'Angelo, N. Kelvin. Phys. Fluids **8**, 1748 (1965)
J. Degrave, F. Felici, J. Buchli et al., Nature **602**, 414 (2022)
P.H. Diamond, T.S. Hahm, Phys. Plasmas **2**, 3640 (1995)
P.H. Diamond, Y.-B. Kim, Phys. Fluids B **3**, 1626 (1991)
P.H. Diamond, Y.-M. Liang, B.A. Carreras, P.W. Terry, Phys. Rev. Lett. **72**, 2565 (1994)
P.H. Diamond, S. Champeaux, M. Malkov et al., Nucl. Fusion **41**, 1067 (2001)
P.H. Diamond, S.-I. Itoh, K. Itoh, T.S. Hahm, Plasma Phys. Control. Fusion **47**, R35 (2005)
P.H. Diamond, S.-I. Itoh, K. Itoh, *Modern Plasma Physics: Vol. 1 Physical Kinetics of Turbulent Plasmas* (Cambridge University Press, Cambridge, 2010)
A.M. Dimits, G. Bateman, M.A. Beer et al., Phys. Plasmas **7**, 969 (2000)
E.J. Doyle, R.J. Groebner, K.H. Burrell et al., Phys. Fluids B **3**, 2300 (1991)
T.H. Dupree, Phys. Fluids **15**, 334 (1972)
T.H. Dupress, Phys. Rev. Lett. **25**, 789 (1970)
V. Erckmann, F. Wagner, J. Baldzuhn et al., Phys. Rev. Lett. **70**, 2086 (1993)
T. Estrada, T. Happel, C. Hidalgo et al., Europhys. Lett. **92**, 35001 (2010)
T. Estrada, C. Hidalgo, T. Happel, P.H. Diamond, Phys. Rev. Lett. **107**, 245004 (2011)
M.E. Fenstermacher et al., Nucl. Fusion **62**, 042024 (2022)
R.J. Fonck, Phys. Rev. A **29**, 3288 (1984)
R.J. Fonck, G. Cosby, R.D. Durst, S.F. Paul, N. Bretz, S. Scott, E. Synakowski, E. Taylor, Phys. Rev. Lett. **70**, 3736 (1993)
A. Fujisawa et al., Phys. Rev. Lett. **79**, 1054 (1997)
A. Fujisawa et al., Phys. Rev. Lett. **81**, 2256 (1998)
A. Fujisawa et al., Phys. Rev. Lett. **82**, 2669 (1999)
A. Fujisawa, Plasma Phys. Control. Fusion **45**, R1 (2003)
A. Fujisawa et al., Plasma Phys. Control. Fusion **48**, S205 (2006)
A. Fujisawa, Nucl. Fusion **49**, 013001 (2009)
A. Fujisawa, AIP Conf. Proc. **1993**, 020011 (2018)
A. Fujisawa, Proc. Jpn. Acad. Ser B **97**, 103 (2021)
A. Fujisawa, H. Iguchi, S. Lee, T.P. Crowley, Y. Hamada, S. Hidekuma, K. Kojima, Rev. Sci. Instrum. **67**, 3099 (1996)
A. Fujisawa, H. Iguchi, T. Minami et al., Phys. Plasmas **7**, 4152 (2000)
A. Fujisawa, K. Itoh, H. Iguchi et al., Phys. Rev. Lett. **93**, 165002 (2004)
A. Fujisawa, A. Shimizu, H. Nakano, S. Ohshima, Plasma Phys. Control. Fusion **49**, 845 (2007)
A. Fujisawa, K. Itoh, A. Shimizu et al., Phys. Rev. Lett. **98**, 165001 (2007)
A. Fujisawa, T. Ido, A. Shimizu et al., Nucl. Fusion **47**, S718 (2007)
A. Fujisawa, A. Shimizu, H. Nakano, S. Ohshima, K. Itoh et al., J. Phys. Soc. Jpn. **76**, 033501 (2007a)
A. Fujisawa, A. Shimizu, H. Nakano, S. Ohshima et al., Plasma Phys. Control. Fusion **49**, 211 (2007b)
A. Fujisawa, K. Itoh, A. Shimizu et al., Phys. Plasmas **15**, 055906 (2008)
A. Fujisawa, Y. Nagashima, S. Inagaki et al., Plasma Fusion Res. **10**, 1201080 (2015)
A. Fujisawa, Y. Nagashima, S. Inagaki et al., Plasma Phys. Control. Fusion **58**, 25005 (2016)
T. Fujita, Plasma Phys. Control. Fusion **44**, A19 (2002)
T. Fujita, T. Oikawa, T. Suzuki et al., Phys. Rev. Lett. **87**, 245001 (2001)
A. Fukuyama, K. Itoh, S.-I. Itoh, M. Yagi, M. Azumi, Plasma Phys. Control. Fusion **36**, 1385 (1994)
P. Galli, A. Cherubini, R. de Angelis et al., Nucl. Fusion **38**, 1355 (1998)
P. Galli, G. Gorini, P. Manica et al., Nucl. Fusion **39**, 1355 (1999)
X. Garbet et al., Nucl. Fusion **50**, 043002 (2010)
X. Garbet, L. Laurent, A. Samain, J. Chinardet, Nucl. Fusion **34**, 963 (1994)
J. Garcia, R.J. Dumont, J. Joly et al., Nucl. Fusion **59**, 086047 (2019)
K.W. Gentle et al., Phys. Rev. Lett. **74**, 3620 (1995)
E. Gibney, Nature **602**, 371 (2022)
J. Glanz, Science **274**, 1600 (1996)
R.J. Groebner, K.H. Burrell, R.P. Seraydarian, Phys. Rev. Lett. **64**, 3015 (1990)
I. Gruzinov, A. Das, P.H. Diamond, A. Smolyakov, Phys. Lett. A **302**, 110 (2002)
D.K. Gupta, R.J. Fonck, G.R. McKee, D.J. Schlossberg, M.W. Shaffer, Phys. Rev. Lett. **97**, 125002 (2005)
P.N. Guzdar, R.G. Kleva, A. Das, P.K. Kaw, Phys. Rev. Lett. **87**, 015001 (2001)
T.S. Hahm et al., Nucl. Fusion **53**, 072002 (2013)

T.S. Hahm, K.H. Burrell, Phys. Plasmas **2**, 1648 (1995)
T.S. Hahm, P.H. Diamond, J. Korean Phys. Soc. **73**, 747 (2018)
T.S. Hahm, M.A. Beer, Z. Lin, G.W. Hammett, W.W. Lee, W.M. Tang, Phys. Plasma **6**, 922 (1999)
T.S. Hahm, P.H. Diamond, Z. Lin, K. Itoh, S.-I. Itoh, Plasma Phys. Control. Fusion **46**, A323 (2004)
Y. Hamada et al., Nucl. Fusion **45**, 81 (2005)
Y. Hamada, T. Watari, A. Nishizawa, K. Narihara, Y. Kawasumi, T. Ido et al., Phys. Rev. Lett. **96**, 115003 (2006)
A. Hasagawa, M. Wakatani, Phys. Rev. Lett. **59**, 1581 (1987)
A. Hasegawa, Adv. Phys. **34**, 1 (1985)
A. Hasegawa, K. Mima, Phys. Rev. Lett. **39**, 205 (1977)
A.B. Hassam, T.M. Antonsen Jr., J.F. Drake, C.S. Liu, Phys. Rev. Lett. **66**, 309 (1991)
D.E. Hastings, Phys. Fluids **27**, 935 (1984)
C. Hidalgo, C. Silva, M.A. Pedrosa, E. Sánchez, H. Fernandes, C.A.F. Varandas, Phys. Rev. Lett. **83**, 2203 (1999)
M. Hirsch, E. Holzhauer, J. Baldzuhn, B. Kurzan, B. Scott, Plasma Phys. Control. Fusion **43**, 1641 (2001)
G.T. Hoang, C. Bourdelle, X. Garbet, G. Giruzzi, T. Aniel, M. Ottaviani, Phys. Rev. Lett. **87**, 125001 (2001)
C. Holland, G.R. Tynan, R.J. Fonck, G.R. McKee, J. Candy, R.E. Waltz, Phys. Plasmas **14**, 056112 (2007)
M. Hugon et al., Nucl. Fusion **32**, 33 (1992)
K. Ida et al., Phys. Rev. Lett. **76**, 1268 (1996)
K. Ida et al., Nucl. Fusion **39**, 1649 (1999)
K. Ida et al., Phys. Rev. Lett. **91**, 085003 (2003)
K. Ida et al., Nucl. Fusion **55**, 113006 (2015)
K. Ida, T. Fujita, Plasma Phys. Control. Fusion **60**, 03301 (2018)
K. Ida, S. Hidekuma, Y. Miura et al., Phys. Rev. Lett. **65**, 1364 (1990)
K. Ida, M. Yoshinuma, M. Osakabe et al., Phys. Plasmas **16**, 056111 (2009)
K. Ida, T. Kobayashi, K. Itoh, M. Yoshinuma, T. Tokuzawa, T. Akiyama et al., Sci. Rep. **6**, 36217 (2016)
T. Ido et al., Phys. Rev. Lett. **88**, 055006 (2001)
T. Ido et al., Nucl. Fusion **46**, 512 (2006)
T. Ido, K. Kamiya, Y. Miura et al., Plasma Phys. Control. Fusion **42**, A309 (2000)
T. Ido, K. Itoh, M. Osakabe et al., Phys. Rev. Lett. **116**, 015002 (2016)
S. Inagaki et al., Nucl. Fusion **53**, 113006 (2013)
S. Inagaki, K. Ida, N. Tamura et al., Plasma Phys. Control. Fusion **46**, A71 (2004)
S. Inagaki, H. Takenaga, K. Ida et al., Nucl. Fusion **46**, 133 (2006a)
S. Inagaki, N. Tamura, T. Tokuzawa et al., Plasma Phys. Control. Fusion **48**, A251 (2006b)
S. Inagaki, T. Tokuzawa, K. Itoh et al., Phys. Rev. Lett. **107**, 115001 (2011)
S. Inagaki, T. Kobayashi, Y. Kosuga et al., Sci. Rep. **6**, 22189 (2016)
S.-I. Itoh, K. Itoh, A. Fukuyama, Y. Miura, JFT-2M Group, Phys. Rev. Lett. **67**, 2485 (1991)
K. Itoh et al., Phys. Plasmas **14**, 020702 (2007)
K. Itoh et al., Plasma Fusion Res. **11**, 1402002 (2016)
K. Itoh et al., Plasma Phys. Rep. **42**, 418 (2016)
K. Itoh, Plasma Phys. Control. Fusion **62**, 020101 (2020)
S.-I. Itoh, K. Itoh, Phys. Rev. Lett. **60**, 2276 (1988)
K. Itoh, S.-I. Itoh, Plasma Phys. Control. Fusion **38**, 1 (1996)
S.-I. Itoh, K. Itoh, J. Phys. Soc. Jpn. **68**, 1891 (1998)
S.-I. Itoh, K. Itoh, J. Phys. Soc. Jpn. **68**, 2611 (1999)
S.-I. Itoh, K. Itoh, J. Phys. Soc. Jpn. **69**, 408 (2000)
S.-I. Itoh, K. Itoh, J. Phys. Soc. Jpn. **69**, 427 (2000)
S.-I. Itoh, K. Itoh, J. Phys. Soc. Jpn. **69**, 3253 (2000)
S.-I. Itoh, K. Itoh, Sci. Rep. **2**, 860 (2012)
S.-I. Itoh, K. Itoh, Nucl. Fusion **53**, 073035 (2013)
K. Itoh, S.-I. Itoh, Plasma Phys. Control. Fusion **58**, 045017 (2016)
S.-I. Itoh, K. Itoh, Nucl. Fusion **56**, 106028 (2016)
K. Itoh, S.-I. Itoh, AIP Conf. Proc. **1993**, 020012 (2018)
K. Itoh, S.-I. Itoh, Plasma Fusion Res. **14**, 3403058 (2019)
K. Itoh, S.-I. Itoh, A. Fukuyama, K. Hanatani, Nucl. Fusion **29**, 1851 (1989)

K. Itoh, H. Sanuki, J. Todoroki, T. Kamimura, S.-I. Itoh, A. Fukuyama, K. Hanatani, Phys. Fluids B **3**, 1294 (1991)
K. Itoh, S.-I. Itoh, A. Fukuyama, Phys. Rev. Lett. **69**, 1050 (1992a)
K. Itoh, S.-I. Itoh, A. Fukuyama, M. Yagi, M. Azumi, Plasma Phys. Control. Fusion **36**, 279 (1992b)
K. Itoh, S.-I. Itoh, A. Fukuyama, M. Yagi, M. Azumi, Plasma Phys. Control. Fusion **36**, 1501 (1992c)
K. Itoh, S.-I. Itoh, A. Fukuyama, H. Sanuki, M. Yagi, Plasm Phys. Control. Fusion **36**, 123 (1994a)
S.-I. Itoh, K. Itoh, A. Fukuyama, M. Yagi, Phys. Rev. Lett. **72**, 1200 (1994b)
S.-I. Itoh, K. Itoh, A. Fukuyama, J. Nucl. Mater. **117**, 220 (1995)
S.-I. Itoh, K. Itoh, A. Fukuyama, M. Yagi, Phys. Rev. Lett. **76**, 920 (1996)
S.-I. Itoh, K. Itoh, H. Zushi, A. Fukuyama, Plasma Phys. Control. Fusion **49**, 879 (1998)
K. Itoh, S.-I. Itoh, M. Yagi, A. Fukuyama, Phys. Plasma **5**, 4121 (1998)
K. Itoh, S.-I. Itoh, A. Fukuyama, *Transport and Structural Formation in Plasmas* (Institute of Physics Publishing, Bristol, 1999)
K. Itoh, K. Hallatschek, S.I. Itoh, Plasma Phys. Control. Fusion **47**, 451 (2005)
K. Itoh, Y. Nagashima, S.-I. Itoh et al., Phys. Plasma **12**, 102301 (2005)
K. Itoh, S.-I. Itoh, P.H. Diamond, T.S. Hahm et al., Phys. Plasmas **13**, 055502 (2006)
K. Itoh, S.-I. Itoh, P.H. Diamond et al., Plasma Fusion Res. **1**, 037 (2006)
S.-I. Itoh, K. Itoh, M. Sasaki, A. Fujisawa, T. Ido, Y. Nagashima, Plasma Phys. Control. Fusion **49**, L7 (2007)
S.-I. Itoh, S. Nishimura, K. Itoh et al., Plasma Fusion Res. **4**, 014 (2009)
S.-I. Itoh, K. Itoh, Y. Nagashima, Y. Kosuga, Plasma Fusion Res. **12**, 1101003 (2017)
K. Itoh, S.-I. Itoh, M. Sasaki, Y. Kosuga, Nucl. Fusion **57**, 056031 (2017)
G.L. Jackson, J. Winter, T.S. Taylor et al., Phys. Rev. Lett. **67**, 3098 (1991)
M. Jakubowski, R.J. Fonck, G.R. McKee, Phys. Rev. Lett. **89**, 265003 (2009)
F.C. Jobes, R.L. Hickok, Nucl. Fusion **10**, 195 (1970)
B.B. Kadomtsev, O.P. Pogutse, Phys. Rev. Lett. **25**, 1155 (1970)
B.B. Kadomtsev, O.P. Pogutse, Nucl. Fusion **11**, 67 (1971)
K. Kamiya, K. Itoh, S.-I. Itoh, Sci. Rep. **6**, 30585 (2016)
K. Kamiya, K. Itoh, S.-I. Itoh, Nucl. Fusion **57**, 126003 (2017)
N. Kasuya et al., Phys. Plasmas **15**, 052302 (2008)
N. Kasuya et al., Nucl. Fusion **58**, 106033 (2018)
N. Kasuya, K. Itoh, Phys. Rev. Lett. **94**, 195002 (2005)
P. Kaw et al., Plasma Phys. Control. Fusion **44**, 51 (2002)
S.M. Kaye, R.J. Goldston, Nucl. Fusion **25**, 112765 (1985)
E.-J. Kim, P.H. Diamond, Phys. Rev. Lett. **90**, 185006 (2003)
J.S. Kim, R.D. Curst, R.J. Fonck et al., Phys. Plasmas **3**, 3998 (1996)
J.S. Kim, R.J. Fonck, R.D. Durs et al., Phys. Rev. Lett. **79**, 841 (1997)
F. Kin, K. Itoh, A. Fujisawa et al., Phys. Plasmas **25**, 062304 (2018)
F. Kin, A. Fujisawa, K. Itoh et al., Phys. Plasmas **26**, 042306 (2019)
D.A. Kislov, T-10 Team, Nucl. Fusion **41**, 1473 (2001)
M.W. Kissick, J.D. Callen, E.D. Fredrickson, A.C. Janos, G. Taylor, Nucl. Fusion **36**, 1691 (1996)
T. Klinger, T. Andreeva, S. Bozhenkov et al., Nucl. Fusion **59**, 112004 (2019)
T. Kobayashi et al., Phys. Rev. Lett. **120**, 045002 (2018)
M. Kobayashi et al., Phys. Rev. Lett. **128**, 125001 (2022)
T. Kobayashi, S. Inagaki, H. Arakawa et al., Plasma Fusion Res. **5**, S2047 (2010)
T. Kobayashi, S. Inagaki, H. Arakawa et al., Plasma Fusion Res. **6**, 2401082 (2011)
T. Kobayashi, S. Inagaki, H. Arakawa et al., Plasma Fusion Res. **7**, 2401054 (2012)
T. Kobayashi, K. Itoh, T. Ido, K. Kamiya, S.-I. Itoh, Y. Miura et al., Phys. Rev. Lett. **111**, 035002 (2013)
T. Kobayashi, S. Inagaki, M. Sasaki et al., Plasma Fusion Res. **12**, 1401019 (2017)
T. Kobayashi, H. Takahashi, K. Nagaoka et al., Sci. Rep. **9**, 15913 (2019)
T.-K. Kobayashi, A. Fujisawa, Y. Nagashima et al., Plasma Phys. Control. Fusion **63**, 032001 (2021)
Y. Koide, M. Kikuchi, M. Mori et al., Phys. Rev. Lett. **72**, 3662 (1994)
Y. Kosuga et al., Plasma Phys. Control. Fusion **55**, 125001 (2013)
Y. Kosuga et al., Phys. Plasmas **24**, 032304 (2017)
Y. Kosuga et al., Nucl. Fusion **57**, 072006 (2017)
Y. Kosuga et al., Phys. Plasma **27**, 022303 (2020)
Y. Kosuga et al., Phys. Plasmas **29**, 122301 (2022)
Y. Kosuga, P.H. Diamond, Phys. Plasmas **19**, 07307 (2012)

Y. Kosuga, P.H. Diamond, Ö.D. Gürcan, Phys. Rev. Lett. **110**, 105002 (2013)

Y. Kosuga, S.-I. Itoh, K. Itoh, Plasma Fusion. Res. **10**, 3401024 (2015)

L.M. Kovrizhnykh, Nucl. Fusion **24**, 435 (1984)

A. Krämer-Flecken, S. Soldatov, H.R. Koslowski, O. Zimmermann, TEXTOR Team, Phys. Rev. Lett. **97**, 045006 (2006)

J.E. Lee, G.S. Yun, W. Lee et al., Sci. Rep. **7**, 45075 (2017)

M. Lesur et al., Phys. Plasmas **24**, 012511 (2017)

M. Lesur, K. Itoh, T. Ido et al., Phys. Rev. Lett. **116**, 015003 (2016)

F.M. Levinton, R.J. Fonck, G.M. Gammel et al., Phys. Rev. Lett. **63**, 2060 (1989)

F.M. Levinton, M.C. Zarnstorff, S.H. Batha et al., Phys. Rev. Lett. **75**, 4417 (1995)

P.C. Liewer, Nucl. Fusion **25**, 542 (1985)

Z. Lin, T.S. Hahm, W.W. Lee, W.M. Tang, R.B. White, Science **281**, 1835 (1998)

N. J. Lopes Cardozo, Plasma Phys. Control. Fusion **37**, 799 (1995)

T. Luce, C.C. Petty, J.C.M. de Haas, Phys. Rev. Lett. **68**, 52 (1992)

H. Maassberg, C.D. Beidler, U. Gasparino et al., Plasma Phys. Control. Fusion **7**, 295 (2000)

W.M. Manheimer, T.M. Antonsen, Phys. Fluids **22**, 957 (1979)

M.E. Manso, Plasma Phys. Control. Fusion **35**, B141 (1993)

P. Mantica, P. Galli, G. Gorini et al., Phys. Rev. Lett. **82**, 5048 (1999)

P. Manz, M. Ramisch, U. Stroth, V. Naulin, B.D. Scott, Plasma Phys. Control. Fusion **50**, 035008 (2008)

P. Manz, M. Ramisch, U. Stroth, Plasma Phys. Control. Fusion **51**, 035008 (2009)

P. Manz, M. Ramisch, U. Stroth, Phys. Rev. Lett. **103**, 165004 (2009)

N. Mattor, P.H. Diamond, Phys. Rev. Lett. **72**, 486 (1994)

E. Mazzucato, Rev. Sci. Instrum. **69**, 2201 (1998)

E. Mazzucato, R. Nazikian, Phys. Rev. Lett. **71**, 1840 (1993)

K. McCormick et al., Phys. Rev. Lett. **89**, 15001 (2002)

G.R. Mckee et al., Plasma Phys. Control. Fusion **45**, A477 (2003)

A.V. Melnikov et al., Plasma Phys. Control. Fusion **48**, S87 (2006)

A.M. Messian et al., Phys. Rev. Lett. **77**, 2487 (1996)

Y. Miura, T. Ido, K. Kamiya, Y. Hamada, JFT-2M Group, Nucl. Fusion **41**, 973 (2001)

C. Moon, K. Yamasaki, Y. Nagashima et al., Sci. Rep. **11**, 3720 (2021)

S. Morita et al., Plasma Physics and Controlled Fusion Research (*Proc. 14th Int. Conf., Würzburg, 1992*) vol. 2 (Vienna: IAEA), p. 515 (1993)

R.A. Moyer et al., Phys. Plasmas **2**, 2397 (1995)

R.A. Moyer, G.R. Tynan, C. Holland, M.J. Burin, Phys. Rev. Lett. **87**, 135001 (2001)

Y. Nagashima et al., Plasma Phys. Control. Fusion **48**, S1 (2006)

Y. Nagashima et al., Plasma Phys. Control. Fusion **51**, 065019 (2009)

Y. Nagashima, K. Hoshino, A. Ejiri et al., Phys. Rev. Lett. **95**, 095002 (2005)

Y. Nagashima, S.-I. Itoh, S. Shinohara, M. Fukao et al., Plasma Fusion Res. **3**, 056 (2008)

Y. Nagashima, S.-I. Itoh, S. Shinohara et al., Phys. Plasmas **16**, 020706 (2009)

Y. Nagashima, S. Inagaki, K. Kamataki et al., Rev. Sci. Instrum. **82**, 033503 (2011)

Y. Nagashima, S.-I. Itoh, S. Inagaki, H. Arakawa, N. Kasuya, A. Fujisawa et al., Phys. Plasmas **18**, 070701 (2011)

Y. Nagayama, J. Appl. Phys. **62**, 2702 (1987)

Y. Nagayama et al., Phys. Rev. Lett. **61**, 1839 (1988)

D.E. Newman, B.A. Carreras, P.H. Diamond, T.S. Hahm, Phys. Plasmas **3**, 1858 (1996)

K. Nozaki, T. Taniuti, K. Watanabe, J. Phys. Soc. Jpn. **46**, 991 (1979)

R. Numata et al., Phys. Plasmas **14**, 102312 (2007)

N. Ohyabu, T. Morisaki, S. Masuzaki et al., Phys. Rev. Lett. **97**, 055002 (2006)

N. Ohyama, A. Fujisawa, S. Inagaki et al., **7**, 1201025 (2012)

S. Oldenbürger, S. Inagaki, T. Kobayashi, H. Arakawa, N. Ohyama, K. Kawashima, Y. Tobimatsu, A. Fujisawa, K. Itoh, S.-I. Itoh, Plasma Phys. Control. Fusion **54**, 055002 (2012)

H.K. Park, A.J.H. Donné, N.C. Luhmann Jr. et al., Phys. Rev. Lett. **96**, 195004 (2006)

C.C. Petty, M.R. Wade, J.E. Kinsey, R.J. Groebner, T.C. Luce, G.M. Staebler, Phys. Rev. Lett. **83**, 3661 (1999)

P.A. Politzer, Phys. Rev. Lett. **84**, 1192 (2000)

C.P. Ritz, E.J. Powers, R.D. Bengston, Phys. Fluids B **1**, 153 (1989)

C.P. Ritz, E.J. Powers, R.D. Bengston, Phys. Fluids B **1**, 153 (1989)

M.N. Rosenbluth, F.L. Hinton, Phys. Rev. Lett. **80**, 724 (1998)

V. Rozhanski, M. Tendler, Phys. Fluids B **4**, 1877 (1992)
V. Rozhansky, M. Tendler, Phys. Plasmas **4**, 1877 (1992)
F. Ryter, F. Leuterer, G. Pereverzev et al., Phys. Rev. Lett. **86**, 2325 (2001)
H. Sanuki, K. Itoh, S.-I. Itoh, J. Phys. Soc. Jpn. **62**, 123 (1993)
M. Sasaki et al., Phys. Plasmas **16**, 022306 (2009)
M. Sasaki et al., Sci. Rep. **7**, 1 (2017)
M. Sasaki et al., Nucl. Fusion **57**, 036025 (2017)
M. Sasaki et al., Plasma Fusion Res. **13**, 3403040 (2018)
M. Sasaki, K. Itoh, S.-I. Itoh, Plasma Phys. Control. Fusion **53**, 085017 (2011)
M. Sasaki, N. Kasuya, K. Itoh et al., Phys. Plasmas **24**, 112103 (2017)
M. Sasaki, K. Itoh, T. Kobayashi et al., Nucl. Fusion **58**, 112005 (2018)
L. Schmitz, Nucl. Fusion **57**, 025003 (2017)
L. Schmitz, L. Zeng, T.L. Rhodes et al., Phys. Rev. Lett. **108**, 155002 (2012)
P.M. Schoch et al., Rev. Sci. Instrum. **74**, 1846 (2003)
P.M. Schoch, A. Carnevali, K.A. Conner, T.P. Crowley, J.C. Forster, R.L. Hickok, J.F. Lewis, J.G. Schatz Jr., G.A. Hallock, Rev. Sci. Instrum. **59**, 1646 (1988)
B.D. Scott, Phys. Rev. Lett. **65**, 3289 (1990)
B.D. Scott, Phys. Fluids B **4**, 2468 (1992)
M. Shafer, G.R. McKee, M.E. Austin et al., Phys. Rev. Lett. **103**, 075004 (2004)
K.C. Shaing, G.S. Lee, B. A. Carreras, W.A. Houlberg, E.C. Crume, Jr., *Proceedings of 12th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, Nice (International Atomic Energy Agency, Vienna, 1989), vol. 2 p. 13 (1988)
K.C. Shaing, E. Crume Jr., Phys. Rev. Lett. **63**, 2369 (1989)
K.C. Shaing, R.D. Hazeltine, H. Sanuki, Phys. Fluids B **4**, 404 (1992)
M.G. Shats et al., Phys. Rev. Lett. **88**, 45001 (2002)
M.G. Shats, W.M. Solomon, H. Xia, Phys. Rev. Lett. **90**, 125002 (2003)
I. Shesterikov, Y. Xu, G.R. Tynan et al., Phys. Rev. Lett. **111**, 055006 (2013)
S. Shinohara, T. Hada, T. Motomura et al., J. Plasma Fusion Res. **16**, 057104 (2009)
F.X. Soldner et al., Phys. Rev. Lett. **61**, 1105 (1988)
W.M. Solomon, M.G. Shats, Phys. Rev. Lett. **87**, 195003 (2001)
J.D. Strachan et al., Phys. Rev. Lett. **58**, 1004 (1987)
E.J. Strait, L.L. Lao, M.E. Mauel et al., Phys. Rev. Lett. **75**, 4421 (1995)
T.E. Stringer, Nucl. Fusion **33**, 1249 (1993)
U. Stroth, Plasma Phys. Control. Fusion **40**, 9 (1998)
U. Stroth et al., Phys. Rev. Lett. **86**, 5910 (2001)
U. Stroth et al., Nucl. Fusion **62**, 042006 (2022)
S. Sudo, Y. Takeiri, H. Zushi, F. Sano, K. Itoh, K. Kondo, A. Iiyoshi, Nucl. Fusion **30**, 11 (1990)
N. Tamura, S. Inagaki, K. Tanaka et al., Nucl. Fusion **47**, 449 (2007)
R.J. Taylor, M.L. Brown, B.D. Fried, H. Grote, J.R. Liberati, G.J. Morales, P. Pribyl, D. Darrow, M. Ono, Phys. Rev. Lett. **63**, 2365 (1989)
S. Toda, K. Itoh, A. Fujisawa, S.-I. Itoh, M. Yagi, A. Fukuyama, P.H. Diamond, Nucl. Fusion **47**, 914 (2007)
K. Toi, S. Okamura, H. Iguchi et al., *Proceedings of 14th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, Würzburg, 1992, (Vienna: IAEA), vol. 2 p. 461 (1993)
T. Tokuzawa, Nucl. Fusion **57**, 025001 (2017)
T. Tokuzawa, S. Inagaki, K. Ida et al., Phys. Plasma **21**, 055904 (2014)
J. Tollefson, E. Gibney, Nature **612**, 597 (2022)
G.R. Tynan, R.A. Moyer, M.J. Burin, C. Holland, Phys. Plasmas **8**, 1691 (2001)
G.R. Tynan, A. Fujisawa, G. McKee, Plasma Phys. Control. Fusion **51**, 113001 (2009)
T. Ullman, B. Schimid, P. Manz et al., Phys. Rev. E **102**, 063201 (2020)
B.P. van Milligen, E. de la Luna, F.L. Tabarés et al., Nucl. Fusion **42**, 787 (2002)
B.P. van Milligen, C. Hidalgo, E. Sánchez, Phys. Rev. Lett. **74**, 395 (1995)
F. Wagner et al., Plasma Phys. Control. Fusion **36**, A61 (1994)
F. Wagner, U. Stroth, Plasma Phys. Control. Fusion **35**, 1321 (1993)
F. Wagner, G. Becker, K. Behringer et al., Phys. Rev. Lett. **49**, 1408 (1982)
W. Wagner, M. Hirsch, H.-J. Hartfuss, H.P. Laqua, H. Maassberg, Plasma Phys. Control. Fusion **48**, A271 (2006)

R.E. Waltz, G.D. Kerbel, J. Milovich, G.W. Hammett, Phys. Plasmas **1**, 2229 (1994)
R.E. Waltz, G.M. Staebler, W. Dorland, G.W. Hammett, M. Kotschenreuther, J.A. Konings, Phys. Plasmas **4**, 2482 (1997)
R.E. Waltz, M.E. Austin, K.H. Burrell, J. Candy, Phys. Plasmas **13**, 052301 (2006)
H. Wang, Hao et al., Phys. Rev. Lett. **120**, 175001 (2018)
R.R. Weynants, G. Van Oost, G. Bertschinger et al., Nucl. Fusion **32**, 837 (1992)
D.G. Whyte, A.E. Hubbard, J.W. Hughes et al., Nucl. Fusion **50**, 105005 (2010)
K.L. Wong, N.L. Bretz, T.S. Hahm, E. Synakowski, Phys. Lett. A **236**, 339 (1997)
A.J. Wootton, B.A. Carreras, H. Matsumoto et al., Phys. Fluids B **2**, 2879 (1990)
H. Xia, M.G. Shats, Phys. Rev. Lett. **91**, 155001 (2003)
Y.H. Xu, C.X. Yu, J.R. Luo et al., Phys. Rev. Lett. **84**, 3867 (2000)
G.S. Xu, B.N. Wan, M. Song, J. Li, Phys. Rev. Lett. **91**, 125001 (2003)
M. Xu, G.R. Tynan, C. Holland, Z. Yan, S.H. Muller, J.H. Yu, Phys. Plasmas **17**, 032311 (2010)
G.S. Xu, B.N. Wan, H.W. Wang et al., Phys. Rev. Lett. **107**, 125001 (2011)
Y. Xu, C. Hidalgo, I. Shesterikov et al., Phys. Rev. Lett. **110**, 265005 (2013)
M. Yagi, K. Itoh, S.-I. Itoh et al., Phys. Fluids B **5**, 3702 (1993)
M. Yagi, K. Itoh, S.-I. Itoh, A. Fukuyama, M. Azumi, J. Phys. Soc. Jpn. **63**, 10 (1994)
M. Yagi, S.-I. Itoh, K. Itoh et al., Phys. Plasmas **2**, 4140 (1995)
T. Yamada, Y. Nagashima, S. Inagaki et al., Rev. Sci. Instrum. **78**, 123501 (2007)
T. Yamada, S.-I. Itoh, T. Maruta et al., Nat. Phys. **4**, 721 (2008)
T. Yamada, S.-I. Itoh, S. Inagaki et al., Phys. Rev. Lett. **105**, 225002 (2010)
T. Yamada, S. Inagaki, M. Sasaki et al., J. Phys. Soc. Jpn. **87**, 034501 (2018)
H. Yamada, K. Tanaka, R. Seki et al., Phys. Rev. Lett. **123**, 185001 (2019)
K. Yamasaki, A. Fujisawa, Y. Nagashima et al., Rev. Sci. Instrum. **91**, 33502 (2020)
Z. Yan, G.R. McKee, R. Fonck et al., Phys. Rev. Lett. **112**, 1125002 (2014)
A. Yoshizawa, S.-I. Itoh, K. Itoh, *Plasma and Fluid Turbulence* (Institute of Physics Publishing, Bristol, 2003)
G.S. Yun, W. Lee, J.J. Choi, H.K. Park, B. Tobias, C.W. Domier et al., Phys. Rev. Lett. **107**, 045004 (2011)
K.J. Zhao, T. Lan, J.Q. Dong et al., Phys. Rev. Lett. **96**, 255004 (2006)
H. Zohm, Phys. Rev. Lett. **72**, 222 (1994)