

Selected contributions to the 15th International Stellarator Workshop from the LHD experiment

1. MHD studies in high- β plasmas

Plasma aspect ratio A_p in the Large Helical Device (LHD) was varied from 6.3–8.3 in order to optimize the configuration for high- β plasma production and to investigate MHD characteristics. The experiment has realized a maximum average β of 4.3% in the $A_p = 6.6$ configuration. The Shafranov shift Δ/a decreased with an increase in A_p at the same β . With $A_p = 6.6$ and $\langle \beta_{dia} \rangle \sim 4\%$, the Δ/a is about 0.2, which is much smaller than the approximate β limit, defined as $\Delta/a = 1/2$.

MHD activities in the periphery are dominantly observed in such a high- β region. Higher electron density enhances such MHD activities, as shown in Fig. 1, which can be interpreted as a reduction of magnetic Reynolds number (S). A clear dependence of S on the amplitude of MHD modes was observed and is qualitatively consistent with the linear theory of the resistive interchange mode. When the plasma aspect ratio is increased, a minor collapse occurs due to $m/n = 1/1$ mode without rotation. This collapse is enhanced further because the plasma current reduces magnetic shear and degrades the β value by more than 50%. For mode excitation, reduction of magnetic shear is essential rather than the plasma current itself.

Figure 2 shows the mode amplitude in the averaged β and central ϵ diagram. Since edge ϵ is about 1.6 in any A_p configuration, central ϵ is closely related to the magnetic shear around the $\epsilon = 1$ resonance. The mode appears in the high- ϵ region, and clear operating limits of the operations were discovered. This limit is qualitatively consistent with the ideal stability limit. The results are expected to give important information on the operational regimes and the future design of helical fusion reactors, and to contribute to experimental knowledge on ideal and resistive instability.

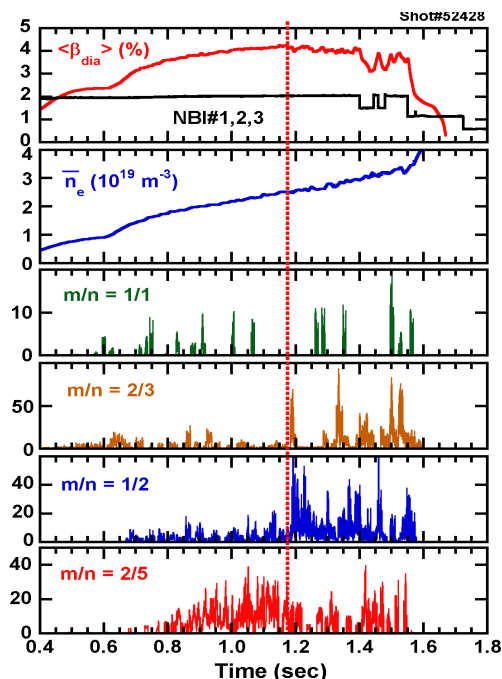


Fig. 1. Typical MHD activities in high- β discharges with $A_p = 6.6$.

In this issue . . .

Selected contributions to the 15th International Stellarator Workshop from the LHD experiment

Major reports at the 15th International Stellarator Workshop from the LHD experiment are outlined. Full descriptions will be available in the special issue of *Fusion Science and Technology*. 1

Two-dimensional turbulence analysis using high-speed visible imaging in TJ-II edge plasmas

Two-dimensional plasma edge turbulence was investigated by means of fast imaging in the visible range. A continuous wavelet-based method was used to localize and study the geometry of coherent turbulent structures (scale, aspect ratio, and orientation angle) in different plasma regimes. 6

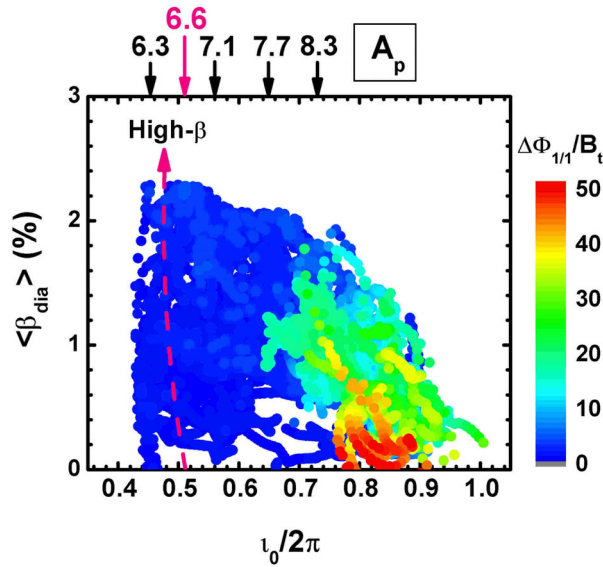


Fig. 2. Appearance of $m/n = 1/1$ mode in the $\langle \beta_{\text{dia}} \rangle$ and t diagram.

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2. Long-pulse plasma discharge experiments using ICRF heating

Long-pulse plasma discharge experiments are an important aspect of LHD. These experiments were carried out primarily using heating in the ion cyclotron range of frequencies (ICRF). The maximum plasma duration is 31 minutes and 45 seconds, and the total injected heating energy reached 1.3 GJ, which is thus far the world record in fusion plasma experimental devices. Figure 3 shows the time evolution of the various experimental data. As shown in Fig. 3(a), ICRF heating is the principal heating mode. Electron cyclotron heating (ECH) and neutral beam injection (NBI) heating are also used to help maintain the plasma discharge. As shown in Figs. 3(b) and 3(c), the electron density is controlled to remain constant and the ion and electron temperatures are almost constant during the plasma discharge, though they are changed by the NBI heating. The radiation loss power is also constant, as shown in Fig. 3(d). Temperatures at the ceramic feedthrough of the antenna and the first wall rise gradually as in, for example, Fig. 3(e). However, they are tolerable in our system. Moving the magnetic axis is adopted as an effective method of scattering the local heat load on the divertor plate during the discharge Fig. 3(f). When the temperature of divertor plate is compared for two different positions, the trends are reversed and the temperature rise is almost saturated. The plasma was terminated abruptly by the influx of metallic impurities accompanied by a spark in the vacuum vessel. There is some relation between the appearance of a high-energy ion tail and the occurrence of sparks. It is proved that the high-energy ions

are few when the density is high. Higher power and higher density operation will be effective to reduce generation of the high-energy ion tail, sparks, and the influx of metal impurities.

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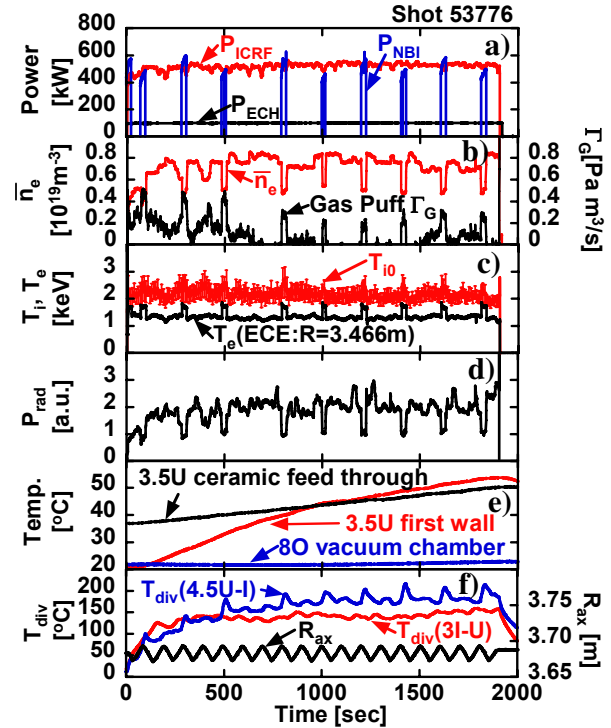


Fig. 3. Waveforms of a 30-min-long discharge with ICRF heating.

3. Effect of magnetic configuration on density fluctuation and particle transport

The characteristics of the particle transport are studied using density modulation experiments in LHD. The roles of fluctuations are investigated from the turbulence measurements using a two-dimensional phase contrast interferometer (2D-PCI). These studies are done under three different magnetic configurations. The experimental values of particle diffusion coefficients (D) and particle convection velocities (V) are compared with neoclassical prediction. The value of D is anomalously large, both in the core, and the edge over the whole configuration scan, and core convection velocities were comparable with the neoclassical estimation in the present experimental regime. There are three kinds of fluctuations, for which the region of existence, propagation direction, and peak wave number are different. Low- k ($\sim 0.4\text{-mm}^{-1}$) fluctuations are localized in the core ($\rho < 0.8$), and higher- k ($\sim 0.8\text{-mm}^{-1}$) fluctuations are localized in the edge ($\rho > 0.8$). Edge high- k fluctuations consist of two components. One is propagat-

ing in the electron diamagnetic direction and the other in the ion diamagnetic direction in the laboratory frame. The ion diamagnetic component shows a clear correlation with edge diffusion. Figure 4 shows density and fluctuation profiles. For a more outward shifted configuration, where edge diffusion becomes larger, the fluctuation amplitude becomes larger under similar average density. However, the growth rate does not vary much, although the diffusion and fluctuation clearly changes. The growth rate is not smallest at $R_{ax} = 3.6$ m, where the fluctuation amplitude and D_{edge} are the smallest. One possible interpretation is a reduction of growth rate or stabilization due to the E_r shearing rate (ω_{E_r}). Figure 4 (d) shows $\gamma_{ITG} - \omega_{E_r}$. The E_r shearing rate was calculated using E_r from GSRake code. The value of $\gamma_{ITG} - \omega_{E_r}$ becomes smaller at $R_{ax} = 3.6$ m, suggesting that a stronger ω_{E_r} helps to reduce fluctuation. However, a more detailed systematic study is required to conclude the identification of the edge ion diamagnetic components and the mechanism of reduced fluctuation at $R_{ax} = 3.6$ m.

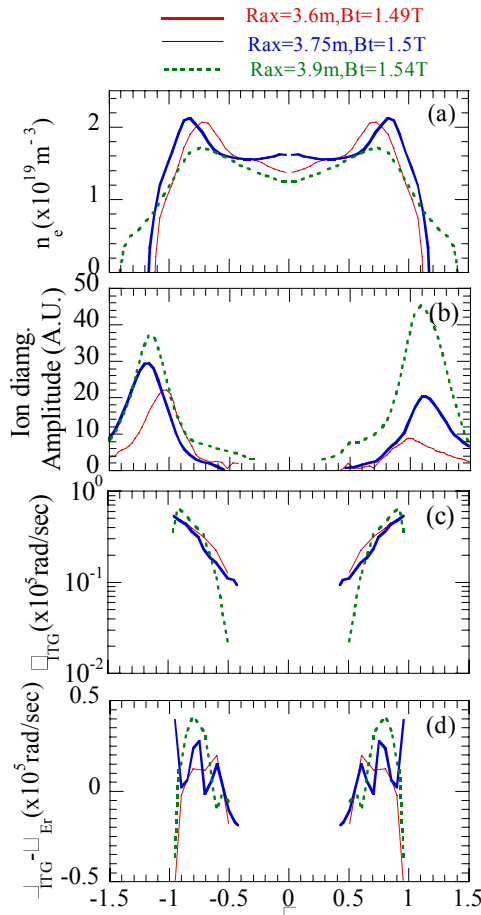


Fig. 4. (a) T_e and n_e profile, (b) fluctuation amplitude profile (c) ITG growth rate, and (d) ITG growth rate minus the E_r shearing rate. $D_{edge} = 0.18, 0.42, \text{ and } 0.57 \text{ m}^2/\text{s}$ at $R_{ax} = 3.6, 3.75, \text{ and } 3.9$ m.

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4. Overview and future plan of helical divertor study

The LHD scrape-off layer (SOL) in the intrinsic helical divertor configuration has a unique magnetic field line structure that contains a stochastic region with residual islands, whisker structures, and laminar layers, contrasting to the “onion-skin”-like magnetic field line structure in the SOL of a poloidal divertor tokamak. Since 1998, the first experimental campaign in LHD, studies aimed at understanding the edge plasma properties in the “open” helical divertor configuration has been conducted experimentally and theoretically to achieve better particle control for improved confinement and the sustainment of a high-performance, steady-state plasma. In this workshop, the progress of helical divertor study in LHD was reviewed. The results are summarized below.

1. The particle and power deposition profiles on the helical divertor (HD) have a three-dimensional structure and are mainly determined by the magnetic structure. In relatively low- β condition, the deposition profiles can be roughly predicted by field line tracing, assuming no plasma. Up-down asymmetry exists, and the reason for this is not clear. The edge MHD activity is found to affect the particle deposition profile. The deposition profiles are modified with increasing β . To predict the particle and power deposition profiles under high- β operation requires new field line tracing codes that take into account the equilibrium.
2. Neutral pressure in the HD is relatively low and is typically between 10^{-4} and 10^{-2} Pa. Particle balance analysis suggests that less than 10% of fueling particles are evacuated by the pumping system, and some fueling particles are retained in the first wall and divertor plates. This builds up during the day as shown in Fig. 5. Therefore, a baffle structure is necessary to achieve effective particle control.
3. A new divertor module with much better thermal properties than the existing one has been developed to achieve long-pulse discharge with high-performance plasmas.
4. Preparation to install a baffle structure and pumping system in the HD is under way. Initial results of neutral particle transport calculations show that several times higher neutral pressure in the HD and a large neutral pressure gradient between the HD region and other volumes can be expected from the DEGAS calculations of Fig. 6.

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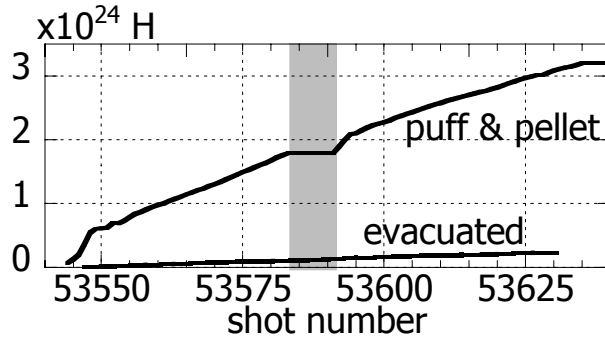


Fig. 5. Gas balance during an experimental day. Shots in the shaded region are without gas puffing.

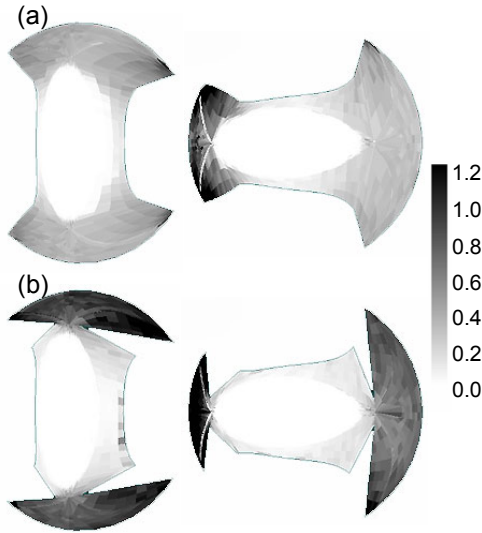


Fig. 6. Density distribution of n_{H_2} calculated with DEGAS Ver. 63 for $R_{ax} = 3.6$ m. (a) Open HD configuration. (b) Closed HD configuration with full helical baffle structure.

5. Observation of self-sustained detachment

Self-sustained detachment, named the “Serpens mode” for self-regulated plasma edge, beneath the last closed flux surface, has been observed in LHD. Typical waveforms from a NBI-heated hydrogen discharge with the Serpens mode phase are shown in Fig. 7. Short massive gas puffing of $\sim 200 \text{ Pa}\cdot\text{m}^3/\text{s}$ is applied at $t \sim 1.1$ s and the electron density at the edge region of $\rho = 0.8$, n_{e08} , is rapidly increased to $> 10^{20} \text{ m}^{-3}$. Then, the radiation loss P_{rad} increases [Fig. 7(a)] and I_{sat} decreases [Fig. 7(b)] significantly, indicating that detachment takes place. The detachment phase (shaded region in Fig. 7) continues without gas puffing until the heating beam stops. Correspondingly, the neutral pressure p_0 [Fig. 7(c)] and the H_α intensity [Fig. 7(d)] also

decrease. These suggest reduced recycling and, at the same time, an improvement in the fueling efficiency for recycling neutrals and/or the particle confinement. Fluctuations appear in P_{rad} , I_{sat} , H_α , and C_{III} signals during the shaded detachment phase. These are strongly correlated with a rotating radiation belt observed on the hot plasma surface, but below the LCFS, which has been named the serpent. The effective hot plasma boundary $\rho_{100 \text{ eV}}$, which denotes the radial position where $T_e = 100 \text{ eV}$, is also plotted in Fig. 7(e). As the detachment proceeds, the hot plasma column shrinks and $\rho_{100 \text{ eV}}$ decreases to ~ 0.9 .

Other states of detachment are also observed; one is “transient partial detachment” and another is “complete detachment.” Figure 8 shows the temporal behavior of $\rho_{100 \text{ eV}}$, I_{sat}^{6-I} measured in the inner gas puff port, and $I_{sat}^{10.5-U}$ measured in the upper port, which is toroidally opposite the gas puff port. Immediately after massive gas puffing ($t = 1.05$ s), I_{sat}^{6-I} significantly decreases, while $I_{sat}^{10.5-U}$ gradually increases with the edge density at $\rho = 0.9$, n_{e09} . This discrepancy between I_{sat}^{6-I} and $I_{sat}^{10.5-U}$ is observed only transiently during massive gas puffing, and therefore we call this “transient partial detachment.” The effective hot plasma boundary ($\rho_{100 \text{ eV}}$) is still outside the LCFS during transient partial detachment. When $\rho_{100 \text{ eV}}$ decreases below 1 ($t \sim 1.16$ s), both I_{sat}^{6-I} and $I_{sat}^{10.5-U}$ begin to decrease, indicating that “complete detachment” takes place. The Serpens mode begins at $t \sim 1.28$ s, when $\rho_{100 \text{ eV}}$ decreases to ~ 0.9 , with appearance of the serpent.

In Wendelstein 7-AS (W7-AS), on the other hand, detachment proceeds as, (1) partial detachment, (2) complete detachment, and, in some cases, (3) Marfe formation. In both devices, radiation collapse terminates the discharge at the highest operational density limit. Transient partial detachment in LHD shares many characteristics with partial detachment in W7-AS, i.e., detachment is partial, there is no clear evidence of high recycling prior to detachment, the neutral pressure in the detached divertor region is of order 0.1 Pa, the plasma column is not shrinking, and the plasma stored energy is not significantly reduced from the attached state. The Serpens mode in LHD, which is a subset of complete detachment, resembles complete detachment and, especially, the Marfe in W7-AS, in the aspects of the fluctuating H_α signal, the radiation belt, the shrinking confinement volume, and the large reduction in the plasma stored energy.

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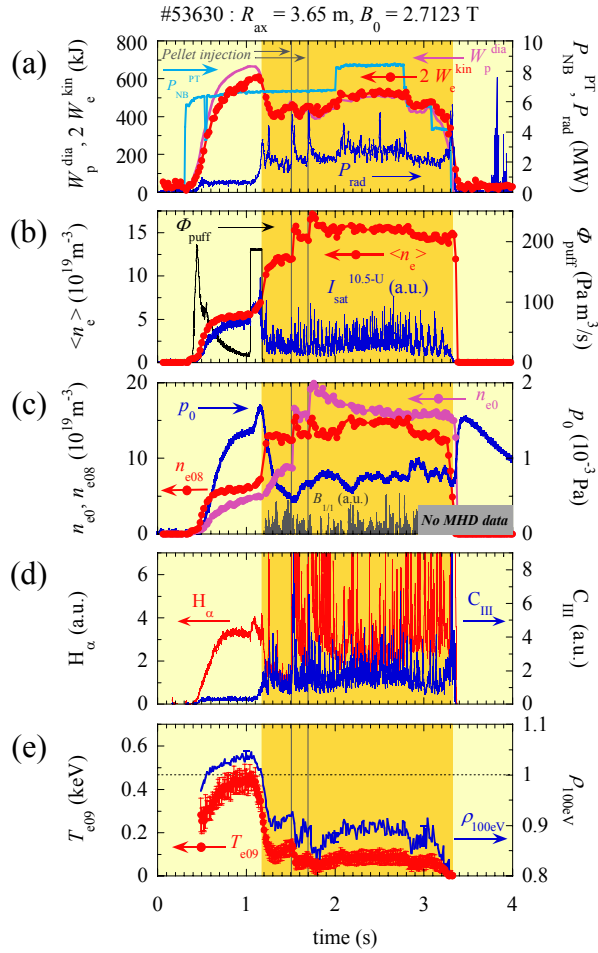


Fig. 7. Waveforms in a typical NBI-heated discharge with the Serpens mode (shaded region, $t = 1.2$ – 3.3 s, denotes complete detachment).

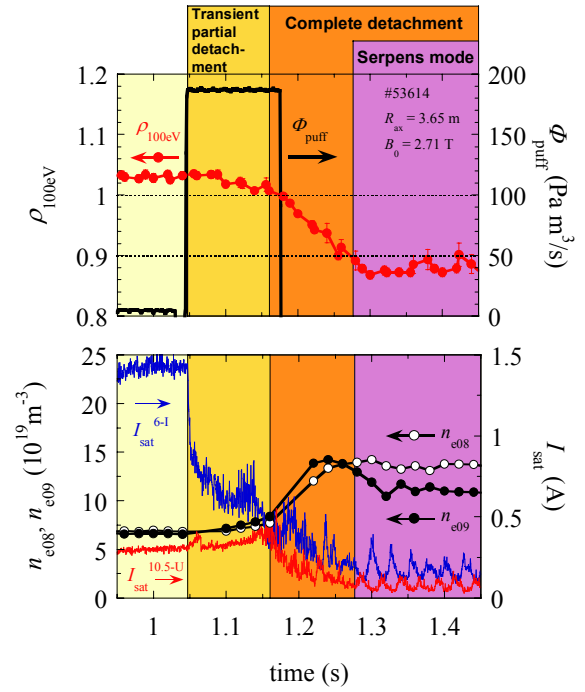


Fig. 8. Waveforms including the transient partial detachment phase ($\rho_{100\text{ eV}} > 1$), the complete detachment phase ($\rho_{100\text{ eV}} < 1$), and the Serpens mode phase ($\rho_{100\text{ eV}} \sim 0.9$).

Two-dimensional turbulence analysis using high-speed visible imaging in TJ-II edge plasmas

1. Introduction

Transport in fusion devices is a phenomenon with a high degree of complexity. Localized layers where $E \times B$ shear stabilization mechanisms are likely playing a role have extensively been proved to have a beneficial impact in confinement. A reduction in turbulence amplitude is expected and measured [1]. However, few attempts have been made to study the effects of such a layer on the morphology of turbulent structures [2]. Two-dimensional (2D) images of edge plasma turbulence have been obtained by high-speed imaging in the visible range in the edge of tokamak devices [3], [4].

This article reports on a 2D visualization of transport in the plasma edge of the TJ-II stellarator by high-speed H_α imaging. A wavelet-based image analysis method is used to localize and characterize blob-like structures. The impact of shear flow and external biasing on turbulent structures is investigated by means of this method.

2. Experimental description

Experiments were carried out in TJ-II plasmas using electron cyclotron resonance heating (ECRH), with $P_{\text{ECRH}} = 200\text{--}400$ kW, $B_T = 1$ T, $R = 1.5$ m, $\langle a \rangle = 0.22$ m, and $\epsilon(a) \approx 1.6$.

For the 2D turbulence studies presented here, two different cameras were used. The first model is a Princeton Scientific Instruments intensified camera with a CCD sensor (PSI-5), achieving recording rates up to 250,000 frames per second (fps). The storage capacity is 300 frames with 64×64 pixel resolution, thus giving 1.2 ms total recording time at maximum speed with an image every 4 ms. The second camera is a Phantom v7.1 by Photo-sonics International LTD, with CMOS sensor. Its recording speed is 120,000 fps with 64×64 pixel frame resolution. Recording durations can be of hundreds of milliseconds.

Neutral recycling at the poloidal limiter is used to light up the outer plasma region ($\rho \sim 0.7\text{--}1$). The view plane is in a near-poloidal cross section with optimized B -field perpendicularity (see Fig. 1). The light cloud extent along field lines was measured and is in the range of a few centimeters (~ 10 cm). Projections of the field lines on the view plane can be seen in the upper left image of Fig. 4.

Bright structures are frequently seen with a spatial extent of a few centimeters. Those structures show predominant poloidal movements with typical speeds of $10^3\text{--}10^4$ ms $^{-1}$,

in agreement with the expected $E \times B$ drift rotation direction. Moreover, projection of the magnetic field lines on the image frame reveals little or no velocity component in the field line direction. With this light cloud thickness, long parallel structures can have a parallel velocity component not visible from the camera position.

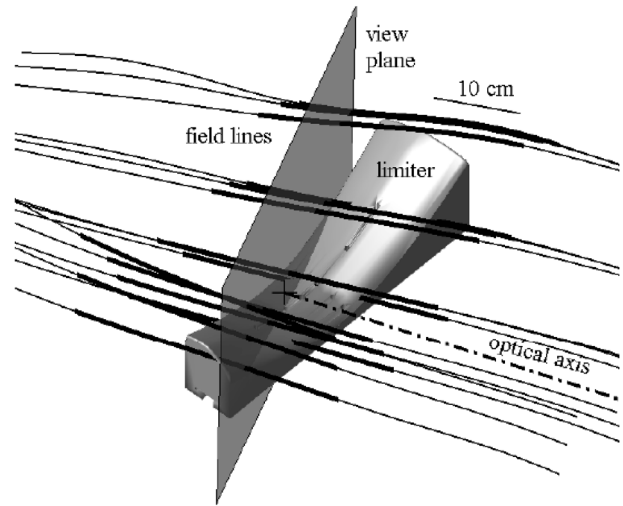


Fig. 1. View plane and field lines near the poloidal limiter used for plasma edge lighting. Broad lines stand for the toroidal extent of the light cloud.

3. Impact of edge shear layer on 2D turbulence structure

A naturally occurring shear layer has been observed in TJ-II edge plasmas [5, 6]. It is self-organized near marginal stability with fluctuations, the shearing rate being close to 10^5 s $^{-1}$. It is formed in certain magnetic configurations above a density threshold ($\sim 0.6 \times 10^{19}$ m $^{-3}$), though its appearance is linked with several magnetic and plasma parameters [6]. The controllable occurrence of this shear layer allows us to study its impact on turbulent structures.

Several image sequences for shots with and without a shear layer were analyzed. Frame size in this series of shots was 11 cm $\times$ 11 cm, and the recording duration was 1.2 ms. During this small time window, line-averaged density is approximately constant.

The method described in Ref. [7] extracts the blobs on three different scales. These detected structures are then analyzed and labeled with a scale, an angle, and an aspect ratio. From the angular and aspect ratio histograms we extract the standard deviation (STD) of angular distribution and the percentage of elongated blobs,¹ respectively. This percentage is a measure of blob stretching, whereas the angular STD is an indication of the level of order of the

1. A blob is considered to be “elongated” when its aspect ratio is greater than 2.

blob population. Large STDs mean that blobs are randomly oriented; small ones mean that blobs point in roughly the same direction.

These blob statistical parameters are plotted against line-averaged electron density in Fig. 2 for the $k \sim 1.2 \text{ cm}^{-1}$ structures (statistics were significant only in this scale). In the top portion of Fig. 2 a clear reduction of angular dispersion is observed as density rises and a shear layer is developed. The bottom portion of Fig. 2. shows a slight though perceptible positive dependence of the percentage “% of elongated blobs” on the line-averaged density.

Mean H_α profiles were measured for these shots. For increasing densities, the images show higher H_α emission, but no reduction of the light cloud, which might be affecting our data interpretation, was observed.

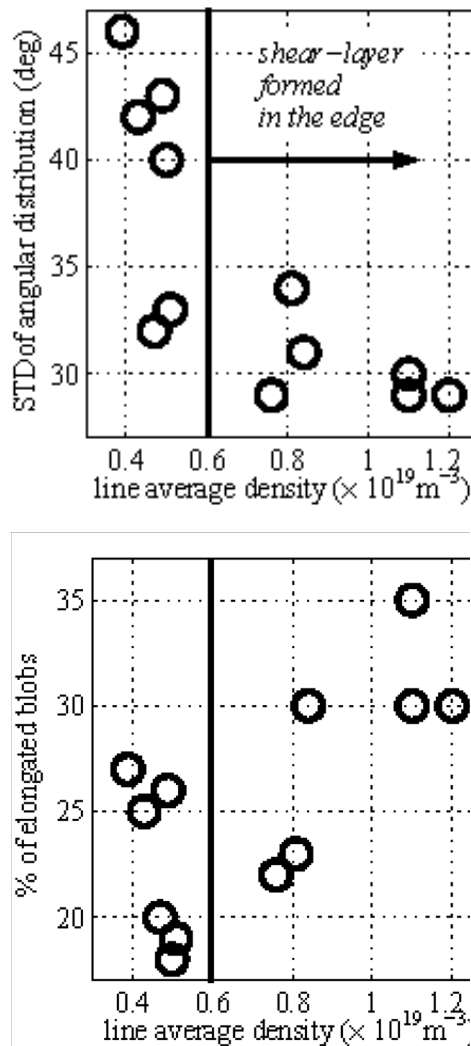


Fig. 2. Density dependence of the standard deviation of blobs angular distribution (top) and population of elongated blobs (bottom).

4. Turbulence structure modification during external biasing induced improved confinement regime

Improved confinement regimes are accessible in the TJ-II stellarator through external biasing [8]. The plasma edge is biased with a graphite electrode installed in a fast reciprocating probe drive. The electrode was inserted typically 2 cm inside the LCFS and biased with respect to one of the two TJ-II limiters [9].

The long recording capabilities of the Phantom v7.1 fast camera allowed us to study the effects of turning off the biasing from the improved to the normal regime. A 17-ms long shot with a $19 \times 19 \text{ cm}$ frame size was analyzed. First results confirm the deep impact of external biasing in plasma edge structures.

Figure 3(a) shows the evolution of the ratio of line-averaged electron density to H_α , evidencing the better confinement during biasing. In this time window, n_e is approximately constant ($\sim 0.6 \times 10^{19} \text{ m}^{-3}$). The frame RMS (calculated as the square root of the sum to every pixel of the squared pixel intensity) reflects the relative increase in turbulence activity [Fig. 3(b)]. The number of turbulent structures detected at all three different scales also increases when biasing is turned off [Figs. 3(c)–3(e)] again reflecting an increase in turbulent activity. However, the increase is not the same for all the analyzed scales, being particularly intense for the intermediate scale ($k \sim 1.4 \text{ cm}^{-1}$). It can be seen that the ratio of medium-scale ($k \sim 1.4 \text{ cm}^{-1}$) to large-scale ($k \sim 0.7 \text{ cm}^{-1}$) blob population changes from 0.4 during biasing to 0.8 after biasing. We emphasize that the number of blobs per frame in each scale is not to be taken as an absolute value, since smaller scales are more affected by noise and therefore the threshold for detection has to be more severe. However, this change in relative scale activity is a meaningful modification of turbulence structure.

The effect of biasing on turbulent structures was also noticeable in the standard deviation (STD) of the angular distribution [for the $k \sim 1.4 \text{ cm}^{-1}$ structures, it changes from 18° during biasing to 29° after it, see Fig. 2(a) for comparison], as well as in the percentage of elongated blobs [from 47% to 34% for $k \sim 1.4 \text{ cm}^{-1}$; see Fig. 2(b)]. A similar tendency was found in the blobs with $k \sim 0.7 \text{ cm}^{-1}$. Not enough $k \sim 2.8 \text{ cm}^{-1}$ structures were detected for significant statistics.

Figure 4 is an example of the structure detection applied to one frame during biasing (upper left image) and after biasing (lower left image). The continuous wavelet transform in three different scales extracts structures around wavelet scale: $k \sim 0.7 \text{ cm}^{-1}$ structures in the second column, $k \sim 1.4 \text{ cm}^{-1}$ in the third column, and $k \sim 2.8 \text{ cm}^{-1}$ in the fourth column. The relative increase can be seen in

medium-scale structures from the frame before biasing turn-off (top) to the frame after biasing (bottom).

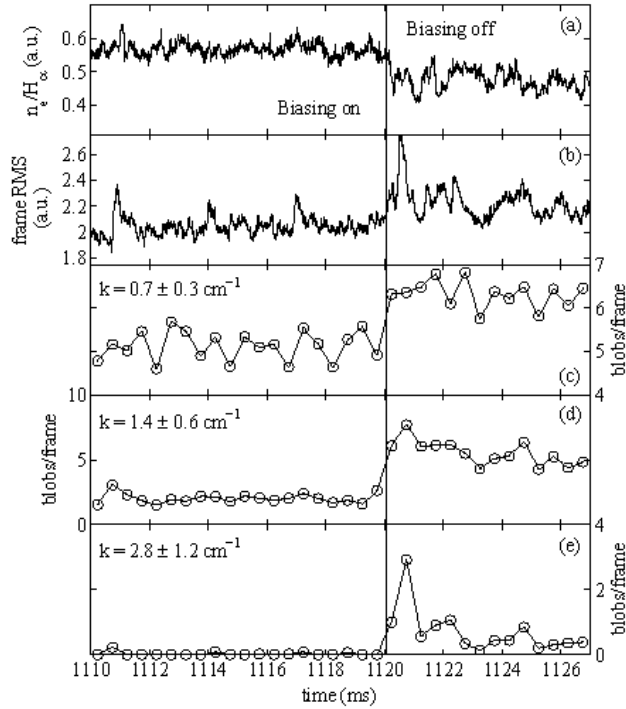


Fig. 3. Time evolution of (a) the ratio of electron density to H_{α} , (b) frame root mean square, and (c)–(e) 50-frame average number of structures per frame in different scales, during and after biasing (shot #13721).

5. Conclusions

Two-dimensional plasma edge turbulence was investigated by means of fast imaging in the visible range. A continuous wavelet-based method was used to localize and study the geometry of coherent turbulent structures (scale, aspect ratio and orientation angle) in different plasma regimes.

First, the impact of the naturally occurring shear layer, self-organized near marginal stability, on TJ-II edge turbulent structures was addressed. Experimental results show a reduction in the angular dispersion of $k \sim 1.2 \text{ cm}^{-1}$ blobs as the shear layer is established in the boundary, as well as a slight though sensible shift of the aspect ratio histogram toward higher values (Fig. 2). These results are consistent with the picture of the shear layer stressing blobs as well as ordering them. Neither significant changes in turbulence intensity (as the number of blobs detected) nor a clear reduction in turbulence scale could be detected with present fast camera experimental setup and analyzing method. It should be noted that spontaneous edge sheared flow and fluctuations are near marginal stability. However, probe measurements show that when sheared flow develops, the level of fluctuations decreases [6].

Second, the effect of external biasing on the blob relative populations of the three different scales analyzed ($k \sim 0.7 \text{ cm}^{-1}$, 1.4 cm^{-1} , 2.8 cm^{-1}) was studied. An increase in all the analyzed scales was observed when biasing was removed. This increase is more noticeable for the intermediate scales, $k \sim 1.4 \text{ cm}^{-1}$. During external biasing the standard deviation of these structures was significantly less than after biasing turn-off, and the aspect ratio histogram was relatively shifted toward higher values. This

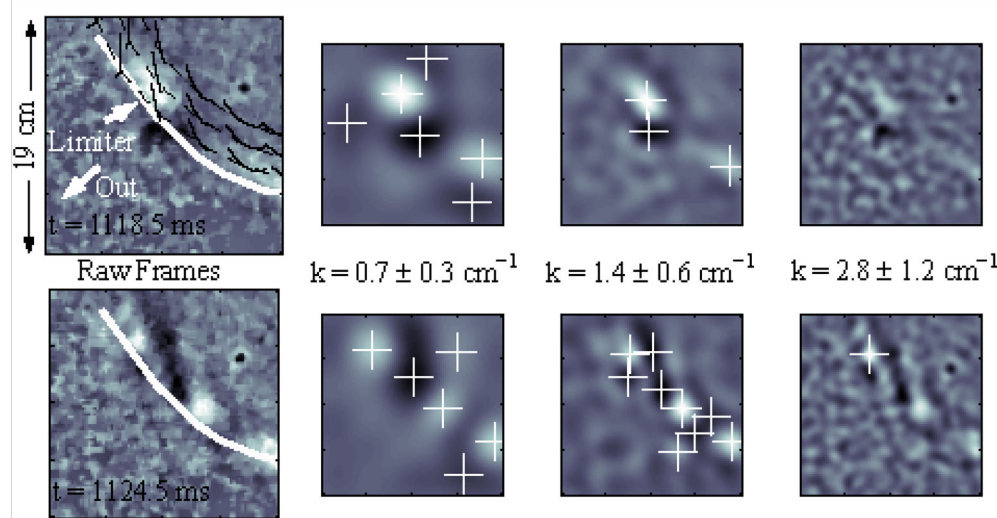


Fig. 4. Structure detection in two frames of shot 13721, during (top) and after biasing (bottom). White pluses indicate detected blob positions. In the upper raw frame: white solid line is the limiter ridge, black dashed lines are the intersections of magnetic surfaces ($\rho \sim 0.65, 0.75, 0.85$) with the view plane, and black solid lines are projections of the magnetic field lines inside the light cloud (30 cm long).

result shows a deep modification in the k power spectrum during external-biasing-induced improved confinement regimes, not only in its integrated power but also in its shape.

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