Life cycle of density structures in a simple magnetized torus

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Abstract. This paper presents an experimental investigation of spatio-temporal structures embedded in the low-frequency electrostatic fluctuations in a toroidal plasma device without rotational transform. The structures are extracted using the conditional averaging technique. The fundamental features and life cycle of the structures from their evolution to demise have been studied. The dipole structures formed rotate in poloidal cross-section with a propagation velocity of \( \sim 9 \times 10^4 \text{ cm s}^{-1} \). The direction of propagation is the same as the electron diamagnetic drift direction and the \( \mathbf{E} \times \mathbf{B} \) rotation direction. We show that these structures evolve in two phases. In the first phase, the spatial extent and the measure of intensity of the structures increase considerably, indicating that ingestion of plasma is more than the loss to the limiter due to diffusion. In the second phase, decay of the structures begins. There are two time scales; the longer one precedes the shorter one. The decay is exponential, indicating that it is solely due to diffusion of plasma to the limiter. This indicates that what appears to be a perpetual periodicity-dominated time series actually consists of a series of large spatio-temporal structures having a definite life cycle of secular growth and decay phases. We interpret this result to mean that BETA plasma possesses a dynamic equilibrium in which the plasma oscillates between two non-equilibrium states.

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1. Introduction

Over the last few decades, considerable work has been done to study the spatio-temporal structures in toroidal devices with an axisymmetric toroidal magnetic field without rotational transform. These devices, known as the simple magnetized torus (SMT), offer good diagnostic access with a relatively simple and inexpensive diagnostic means, long discharge pulses essential for long time series of fluctuations and control over certain parameters of plasma and machine operation. Some of these machines are equipped with very resourceful data acquisition systems dedicating these machines to plasma turbulence. A general feature of the turbulent state exhibited by the toroidal magnetic field configurations is the presence of large coherent structures. These coherent structures have been observed in the plasmas with nearly circular closed [1]–[8] and radially [9, 10] and vertically [11]–[16] elongated open plasma parameter contours. As a consequence of the presence of coherent structures in the plasma, the probability distribution functions (PDFs) of the turbulence in these devices are found to be non-Gaussian. This suggests the existence of intermittency and the bursty nature of plasma transport. However, the role of coherent structures in bringing about plasma transport in the bursts has not been elucidated or has been overlooked.

In this paper, we have attempted to carry out studies in a system where the plasma parameter contours are partially closed within the plasma volume. Using the same analysis tools as those used by other researchers, we delineated the full life cycle of a coherent structure from its evolution to its demise. The evolution of the structures takes place in two phases. In the initial phase, the spatial extent and the measure of intensity of the structure increase to a value where it hesitates for a while till it touches the limiter. At this point, the intensity increases considerably, indicating that ingestion of plasma is more than what is lost because of the diffusion to the limiter. In the later phase, decay of the coherent structures begins. There are two time scales of decay (section 3.3.1); the longer one precedes the shorter one. The decay is exponential, indicating that it is solely due to diffusion of plasma to the limiter.

The paper is organized as follows. Section 2 gives an outline of the experimental setup. Section 3 describes the characteristics of fluctuations and gives the discussion of the life processes of propagating spatio-temporal structures. Finally, the discussion and summary are given in section 4.
2. Experimental setup

The experiments were carried out in a toroidal device, BETA [17]. It consists of a toroidal vacuum chamber of major radius 45 cm and minor radius 15 cm pumped down to a base pressure of $10^{-6}$ torr. A toroidal magnetic field is produced by a set of 16 coils and can be varied up to 1 kG. The experiments presented in this paper were carried out at 200 G. The plasma is produced by a hot cathode filament discharge. A discharge voltage $V_D$ of $\sim 120$ V is applied between a 14 cm long, 2 mm diameter tungsten filament [18] (cathode) and the grounded vessel wall (anode) at a pressure of $10^{-4}$ torr in argon gas. The discharge current in the circuit is $\sim 5$ A. A grounded circular poloidal aperture of 18 cm diameter acting as the limiter defines the size of the plasma column. A schematic diagram of BETA showing the electrical connections and location of the filament and limiter is shown in figure 1. The inset in figure 1 shows the coordinate axes used to represent the poloidal cross-section. The origin (0, 0) of the $XY$ plane is referred to as the center of poloidal cross-section.

Time-averaged plasma parameters and their fluctuations are measured using a movable vertical array of Langmuir probes. The ion saturation current was collected by sufficiently negatively biased probes, floating potential and electron temperature by triple Langmuir probes. The good degree of reproducibility ($\sim 2\%$) of the plasma discharge allows us to construct plasma profiles over the whole cross-section using the data from different probes at different locations with vertical spatial resolution of 1 cm and horizontal resolution of 1 cm. All the measurements have been made at $\sim 180^\circ$ from the filament location. This way we secure 361 independent local measurements of plasma parameters. Figure 2 depicts the poloidal map of the plasma density, plasma potential and electron temperature. The placement of the filament cathode coupled with primary electron drifts dictates the poloidal distribution of various plasma parameters. In this study, the cathode is placed at the center of the poloidal cross-section of the device; therefore, plasma density peaks at approximately the center of the poloidal cross-section ($X = 0.5$ cm, $Y = -1.5$ cm). The electric field ($\sim 40$ V m$^{-1}$) calculated from the floating potential profile gives an $E \times B$ velocity of $\sim 2 \times 10^5$ cm s$^{-1}$. 

Figure 1. Schematic diagram of BETA.
Figure 2. Poloidal maps of (a) electron density, (b) plasma potential and (c) electron temperature.

Ac coupled Langmuir probes were used to measure the fluctuating component of the ion saturation current. After confirming that constant density contours followed $E \times B = \text{constant}$ lines, we concentrated on density fluctuations only for this presentation. The fluctuating parameters from Langmuir probes were sampled simultaneously with a Lecroy digital oscilloscope at 125 kHz with 32 k points per data set, resulting in a 256 ms series with 8 $\mu$s resolution.

To resolve the spatio-temporal dynamics, a pair of time series is recorded at each location of a movable probe ($X_{\text{MP}}$) and a fixed reference probe ($X_{\text{RP}}$). The fluctuations in density are here normalized at each spatial position by the local average density and in potential and temperature by the local temperature. The spatial information is deduced by noting the status of $X_{\text{MP}}$ when a condition in the data $X_{\text{RP}}$ is defined. The defined condition acts as a trigger threshold. Assuming that fluctuations are stationary and ergodic, the defined condition is assumed to be a typical fingerprint of the coherent structure. We have used the simplest and most commonly used amplitude condition and sign of the slope condition of $X_{\text{RP}}$. The slope condition was used to distinguish between the plasma blobs and density holes. We could ensure that coherent structures had amplitudes exceeding the background noise with standard deviation $\sigma (X_{\text{RP}})$.

We write this as

$$X_{\text{MP}}(\tau_i) = X_{\text{MP}1}, X_{\text{MP}2}, X_{\text{MP}3}, \ldots, X_{\text{MP}n}$$

where

$$X_{\text{RP}}(\tau_i) = \kappa \sigma \{X_{\text{RP}1}, X_{\text{RP}2}, X_{\text{RP}3}, \ldots, X_{\text{RP}n} \}$$

and

$$\frac{dX_{\text{RP}}}{dt}|_{\tau_i} > 0 \quad \text{for plasma blobs,}$$

$$< 0 \quad \text{for density holes.}$$
In the data sets for plasma blobs, we could choose $\kappa \geq 1$ as they turned out to be intense. On the other hand, $\kappa$ had to be set as less than 0.5 for density holes.

The indices $\tau_i$ label all data points. The conditional average is then computed by averaging over the ensemble of short time series, which are centered on each $\tau_i$. The time window around this condition is averaged at all locations in the poloidal cross-section with a resolution of 2 cm from 81 repetitive shots. Application of this procedure to all pairs of $X_{MP}$ and $X_{RP}$ results in the spatio-temporal reconstruction. The conditional averaging technique, its advantages and its weaknesses were discussed by Adrian [19]. In BETA, the reference probe is kept at the location where we obtain the maximum fluctuation amplitude (i.e. $r = 5$ cm). The conditions on the reference probe are that of 1.5 $\sigma$ and positive time derivative.

3. Plasma fluctuation characteristics

The fluctuations in density, potential and electron temperature were detected by the Langmuir and triple probes, which were used for the dc measurements. In the time series, there are some repetitive signatures with randomly fluctuating peak amplitudes. Typical frequencies for the fluctuations are below 10 kHz, of the order of the ion cyclotron frequency at 200 G but below it for larger magnetic fields and below the ion plasma frequency. For the numerical analysis, we have formed data sets of 256 ms from a plasma discharge duration of 1.2 s, giving 32 k data points at the sampling rate of 125 kHz.

The plasma state, in currentless toroidal devices like BETA, is strongly influenced by fluctuations. Plasma shows quiescent behavior below the threshold magnetic field of 150 G [17]. Above this threshold magnetic field, it exhibits well-developed fluctuations in plasma parameters in the whole of the plasma cross-section. This suggests the onset of instability beyond this threshold magnetic field, resulting in spontaneously generated normal modes. The dominant instability in the BETA device is believed to be Rayleigh–Taylor or interchange instability [17], [20]–[26]. The amplitudes of density and potential fluctuations have comparable magnitudes. Frequency power spectra of both density and potential fluctuations show oscillations of frequency $\sim 3$ kHz (2.93 $\pm$ 0.24 kHz) together with peaks at integer multiples of this frequency. The frequency of oscillations is an order less than the ion cyclotron frequency. The radial profile of the amplitude of the coherent mode measured at the median plane (i.e. $y = 0$ cm) shows that it maximizes at $x = -3$ and +5 cm. The corresponding $k_\theta$-spectrum shows a coherent peak at 0.41 $\pm$ 0.13 cm$^{-1}$. Taking into account the bandwidths of both frequency and wavenumber, the phase velocity of this coherent peak is $3-7 \times 10^4$ cm s$^{-1}$. The phase difference between azimuthally separated probes establishes that the poloidal mode number is $m = 1$. The phase difference between the density and floating potential fluctuations in the bad curvature region (BCR) is $\sim 163^\circ$. The turbulent state of the plasma is established by the continuous frequency spectrum. The background turbulence in the BETA device follows power law with a spectral index of $\sim -4$ [25].

3.1. Description of time series

3.1.1. Core plasma. As shown in figure 3, positive fluctuations (plasma blobs) are sharper and peaky, whereas negative fluctuations (density holes) are broad with nearly square pulses in the good curvature region (GCR) of core plasma. In the BCR region, repetitive signatures of fluctuations have finer structures. The time series in GCR could be better approximated as
of sinusoidal nature than the time series in BCR and therefore has less spread in the power spectrum compared to the time series in BCR.

3.1.2. Limiter region. Different regions of the limiter (GCR, BCR, top and bottom and right and left of the core plasma) are not distinguishable by the signatures of fluctuations. All the parameters and characteristics of fluctuations in these regions are similar or identical.

3.1.3. Comparison between core and limiter fluctuations. Signatures of core plasma differ from those of the limiter region. For example, fluctuations in the limiter region have significantly reduced coherence, if not completely random. As shown in figure 4, the time series in density fluctuations give nearly Gaussian (amplitude) PDF with a low skewness \( S \sim -0.2 \) to \(-0.28\) and a kurtosis \( K \sim 2.81 - 3.11\), deviating marginally from the value \(3\) that characterizes a Gaussian. This indicates a lack of coherent structures or mode structures in the limiter region.

The onset of fluctuations is not related to the curvature of magnetic field lines in the limiter shadow, which is contrary to our earlier experimental results \([25]\). In these experiments in BETA with a full, conducting termination plate placed at different curved distances from the filament, it is shown that the dominant mode is Rayleigh–Taylor or interchange instability. This instability occurs in the BCR. In this region, curvature drift is antiparallel to the local density gradient, whereas in the GCR the opposite is the case.

PDF in the GCR region significantly deviates from typical Gaussian characteristics with skewness \(~1.12\) and kurtosis \(~3.62\), indicating the predominant occurrence of density holes of...
Figure 4. PDF of time series of unconditioned (without any condition imposed on the reference probe) density fluctuations as a function of amplitude normalized to the maximum amplitude of the reference probe in various regions.

smaller scale lengths. In the BCR region, PDF is bi-modal with a significantly reduced skewness of $\sim 0.58$ and a marginal kurtosis of $\sim 3.51$, showing that there are statistically significant enhancements of fluctuations at positions where the curvature drift is antiparallel to the local density gradient. Bi-modality seems to suggest preferential scale lengths and amplitude sizes for both the plasma blobs and density holes.

Figure 5 shows the PDFs of time series of all plasma regions obtained under the conditions imposed on the reference probe. This time series corresponds to events which had some spatial coherence due to the presence of mode-like structures or coherent spatio-temporal structures in turbulence. We note significant differences from PDFs for unconditioned (by the reference probe) probe data in the BCR region. Bi-modality has largely disappeared. Another significant departure is in the increased PDF values for large-size fluctuations. Combined with the spectral characteristics of fluctuations, we consider this as evidence that the non-Gaussianity of PDFs is largely due to the presence of mode structures rather than coherent structures in turbulence.

3.2. Spectral analysis

Frequency power spectra of density fluctuations, shown in figure 6, do not suggest fully developed turbulence. Both density and potential fluctuations show oscillations of frequency $\sim 3$ kHz ($2.93 \pm 0.24$ kHz) together with peaks at integer multiples of this frequency. These
coherent features are riding over wide-band background turbulence. The frequency of oscillations is an order less than the ion cyclotron frequency ($\sim 50$ kHz). It may be pointed out that the width of the power spectrum can be related to the nature of fluctuation events in time series. The phase difference between azimuthally separated probes establishes that the poloidal mode number is $m = 1$. The turbulent state of the plasma is established by the continuous frequency spectrum. The background turbulence in the BETA device follows power law with the spectral index varying from $\sim -4$ to $-6$ at different radial locations in core plasma. The spectral index in the limiter region is $\sim -2$. The coherence spectrum of fluctuations measured by two probes separated by 1 cm shows high coherence ($\sim 0.8$) corresponding to the peaks in the frequency spectrum in both GCR and BCR [25], whereas coherence ($\sim 0.4$) is low in the limiter region.

### 3.3. Correlation times

Figure 7 shows long time correlations ($\sim 600$ $\mu$s), which is typical for oscillatory or mode-like behavior in core plasma. The auto-correlation functions in both GCR and BCR are similar, indicating no specific feature of mode damping in GCR. Long time correlations in the limiter region are absent, indicating that oscillatory or mode-like behavior is absent in the plasma of the limiter shadow.
3.4. Conditional averaging

We assume that these fluctuations, both plasma blobs and density holes, are propagating localized or intermittent structures in the plasma; their average evolution can be revealed by means of conditional averaging. This information cannot be secured by standard correlation and spectral analyses.

3.4.1. Life processes of coherent structures. We treat fluctuations in BETA plasma as a continuous stream of events of large and small sizes. Only those events are chosen for further study that have values much greater than the average background non-plasma noise, typically about $\sim 5$ dB for the chosen condition of recording events with magnitude greater than $\sigma$, where $\sigma$ is the root mean square associated with the time series from the reference probe. Figure 8 shows the conditional averaging of density fluctuation data at the toroidal magnetic field of 200 G.

The reproducibility of maps shown in figure 8 was tested by two methods. Firstly, a map was produced from entirely different data sets. It was found that the main features of the map are consistent. Secondly, conditional variance was calculated by the standard procedure [1] for different conditions chosen to obtain maps. Small values of variance were noted for high to moderate condition values. For very large condition values, the number of realizations was
low and the statistical uncertainty was large. Very low values of condition were not included. Thus the boundaries of structures in the map were uncertain to some extent. However, the general shape and trajectories, estimated from conditions varying from 0.1 to 2.5σ levels of the structures in the maps, are reliable. We have not observed any structures with contour levels greater than the σ value of 2.5. Also, we have not observed structures with sizes covering the entire plasma diameter. Further, conditionally obtained time series are non-Gaussian. Hence, the non-Gaussian PDF is not contributed by any rare occurrence of large structures or due to preponderance of very small structures due to a lack of adequate spatial resolution.

To prevent plasma from being disturbed by the plasma shaft supporting two Langmuir probes for density and potential and to prevent capacitive effects on the measurement of probe characteristics by high-frequency voltage sweeps, we have not taken simultaneous data on potential and density fluctuations. This has led to a deficiency in the interpretation of our analyses with regard to the identification of potential polarity of plasma blobs and the density holes. Thus, it is not possible to say whether density blobs have a net positive or negative charge. The same is true for density holes.

We note the formation and propagation of a dipole-shaped structure rotating in the $E \times B$ direction around the density peak shown in equilibrium measurements. Positive density blobs seem to be surrounded by density holes. It is observed that small density blobs coalesce into bigger structures as they traverse the transition region from the GCR to the BCR between
Figure 8. Conditional averaging showing spatio-temporal variation of averaged local relative density fluctuations. Solid lines represent positive contours and dotted lines represent negative contours. Dotted circle shows the projection of the limiter in the poloidal cross-section.

\[ \tau = -144 \text{ and } -96 \mu s. \] The evolution time of the density structure is a few \( \mu s. \) Potential structures are similar to density structures.

Figure 9 shows the time–space trajectory of the centroid of a density blob in the poloidal cross-section of plasma. Clearly, blobs are not moving along a closed curve. Blobs spiral out radially. In one poloidal turn, the radial shift is more than 2 cm, which is much greater than the probe-determined spatial resolution of the order of 1 cm. To test whether the observed radial motion is not due to an artifact introduced by making a choice of the centroid of the structure, we have repeated this exercise with centroids of structures with removed central extremum values. Both results are identical. Since the radial velocity is not inferred from the time series measurements on two radially separated probes, our interpretation does not suffer from the defect of converting a purely poloidal motion into an observed radial motion due to asymmetry in the shapes of structures. The calculated radial velocity from figure 9 is \( \sim 60 \text{ m s}^{-1}, \) which is at least an order less than the poloidal velocity. This outward throw of density structures along
Figure 9. Time–space trajectory of the centroid of density structures in the poloidal cross-section. Solid lines represent positive contours and dotted lines represent negative contours. The dotted circle shows the projection of the limiter in the poloidal cross-section.

Figure 10. Size of the positive structure as a function of time. The dotted lines show the instants of time when the structure touches the limiter.

the minor radius may be due to the centrifugal force of $E \times B$ rotation in the poloidal cross-section. The structure formed has a much longer lifetime ($\sim 600 \mu s$) compared to its half turn transit time ($\sim 150 \mu s$) in the plasma cross-section.

Both density blobs and density holes deform slowly in their shape and size. To quantify this deformation, we have calculated various parameters characterizing the observed structures. These parameters are the minor and major axes, the area and the intensity of the observed structures. To estimate the minor and major axes, we have drawn contours of the $(1/e)$th fall from the centroid value, i.e. contour maximum and minimum for each frame. These contours are approximated to nearest ellipses and the corresponding minor and major axes of the ellipses are estimated along two mutually perpendicular axes. Figures 10 and 12 show these axes for positive and negative density structures, respectively. Figures 11 and 13 show the time evolution of the area of structures corresponding to the $(1/e)$th fall from the fluctuation peaks. The intensity
of the density blob or density hole is defined by $\delta I = \int \delta n_0 \delta A \frac{1}{e}$. This integral has been numerically calculated from the observed data set with a mesh size of $10 \times 10 \text{ mm}^2$. Figures 14 and 15 show the intensities of positive and negative structures. In these figures we have marked the time when structures make contact with the limiter. The marking is not accurate since the time interval between two frames of the maps is 48 $\mu$s.

We note their evolutionary phase and their decay phase. It seems that the birth of a structure is within the physical space bounded by the limiter. The evolution of plasma blobs takes place in two phases. A customary growth is followed by saturation (figure 11 for area and figure 14 for intensity) in both area and intensity. The increase in area is due to an all round increase in size as reflected by the increase in both the major and minor axes. Simultaneously, there is an increase in intensity. The saturation does not last longer than 50 $\mu$s. There is an almost exponential threefold increase in intensity. This event is also correlated with the structure coming in the shadow of the limiter. As soon as the structure comes in the shadow of the limiter, we notice first a decay lasting $\sim 64 \mu$s. Emerging out of the shadow of the limiter with reduced orthogonal
extent has area and intensity, the structure, a short lifespan of stability ($\sim 60 \mu s$) before it undergoes the final decay to death.

At this point it is necessary to make some comments on the stability of the density blob. It is presumed that an instability mechanism is responsible for its creation. No matter what is the

**Figure 13.** Time evolution of the area of the negative structure. The dotted lines show the instants of time when the structure touches the limiter.

**Figure 14.** Number of particles in positive structures as a function of time.

**Figure 15.** Deficit of the number of particles from mean values in negative structures as a function of time.
nature of the mechanism, growth of the mode, typically in $<100 \mu s$, should drive the density blob to a saturated state or nonlinearly saturated state. Thereafter, it may persist in this state. Strictly speaking, the density blob observed in BETA is not a static feature of fluctuations. It is continually in the dynamic state. There is growth and there is decay. This growth seems to be in addition to the growth of the mode to the saturated state due to its instability mechanism. Hence the sequence of events in the life of a density blob is a sequel to its formation. These events are generated by its continual interaction with the surrounding plasma and the limiter boundaries. So density blobs are not closed systems.

The life cycle time ($600 \mu s$) lasts much longer than the particle confinement of 200 $\mu s$ and is of the order of the auto-correlation time of $\sim 600 \mu s$. As soon as one density blob decays to the background level of fluctuations, a new one appears. This is apparent from the continuity of the time series of coherent fluctuations. Putting temporal variation of the spatial structure of the density blobs together with the time series of fluctuations, it can be said that these spatio-temporal structures do not have perpetual existence.

During the dynamical changes of density blobs, particularly when they shed the peripheral regions of structures, we have not observed the emergence of any low-$k$ structures or significantly increased ion background temperature.

The density holes are best described by these figures by their lack of any dynamical activity as glaring as in plasma blobs. No monotonic growth is observed. A few oscillations precede their death. No consistent growth or decay is observed. Density holes appear to be an independent entity. No correlated activity with plasma blobs is seen. It seems that the only correlated activity with plasma blobs is that they are always formed together. Once formed, they act independently. We have not been able to track them accurately at their end phase. It is not clear whether they disappear together as they appear together. However, even if they disappear at separate times, the lifespan of a phase when a dipole is converted to a monopole is extremely short. If monopoles exist, they do not appear before the decay phase of structures begins. Such secular variation in the parameters of coherent structures is seen for magnetic fields of 400, 600 and 800 G as well.

It is observed in figure 14 that at $\tau = 96 \mu s$ when the structure touches the limiter for the first time, both the number of particles involved in fluctuations and the area they cover decay exponentially with a time scale of $\sim 64 \mu s$ and when the structure touches the limiter for the second time at $\tau = 240 \mu s$, the time scale reduces to $\sim 48 \mu s$. Since the area of the density blob decays at the same time scale as its intensity and assuming that decay is caused by the perpendicular diffusion in the limiter region, we have estimated $D_\perp \sim 40–52 \text{ m}^2 \text{s}^{-1}$. The estimated value is in reasonable agreement with the lower limit of the predicted range of anomalous perpendicular particle diffusion in BETA plasma.

4. Discussion and summary

As is well known, plasma instabilities tend to have a high growth rate in a limited spectral range. Thus the initial state of fluctuations consists of large-amplitude waves in a narrow band of frequencies and, in some cases, their harmonics. These waves are rendered unstable by nonlinear wave–wave interactions and, in some situations, quasi-linear wave–particle interactions. The former interactions lead to ever increasing bandwidth of fluctuations and eventually to broadband turbulence over several decades of frequency and wave vector. Such a mechanism, namely three wave interactions, leads to energy cascade from low frequency $\omega$, low
wave vector $k$ to high $\omega$, high $k$. It is this mechanism that is the backbone of theories suggested for two-dimensional turbulence in the magnetized plasma. There are theories that predict that the inverse cascade of energy transfer can occur from high wave vectors $k$ to low wave vectors $k$ under some suitable conditions. This mechanism can operate all through the spectral range of frequencies of turbulence. Hence, there is a distinct possibility that spectral energy can condense in the low $k$ regime and give rise to stochastically occurring large coherent structures such as vortex structures [27, 28] and zonal flows [29]–[31]. Such theoretical expectations have far-reaching implications. Firstly, we obtain a model description of plasma turbulence. Secondly, these structures are believed to be the source of the observed intermittent transport in several linear and fusion devices.

The operation of the mechanism of inverse energy cascade has been investigated in various plasma [31]–[35] and fusion devices [36, 37]. Tokamaks [36, 37] have not reported strong evidence for this. Crossley et al [38] claim to have seen inverse energy cascade operating in their quadrupole plasma device even when they have shown that fluctuations in this device do not have broadband spectra. Experimental evidence for the existence of stochastically occurring large-scale coherent structures has been reported for various devices. Xia and Shats [39, 40] have linked them to the inverse cascade process. In this work, they have relied for their conclusions on the technique of seeking cross-correlation functions (CCF) between different components of the spectrum. However, their CCF value ($\sim 0.4$) is marginally significant even though the frequency belonging to coherent structures observed in the H-1 Heliac is widely different from the frequency of the unstable modes of plasma turbulence. Further, signatures of pronounced peaks in the power spectrum are found at frequencies below 10 kHz. Each peak has a bandwidth of a few kHz. They represent mode structures. Fredriksen et al [5] have found periodic occurrence of these structures and the corresponding bursting particle transport. Hence, it is not clear whether the method of CCF is adequate for discriminating between the process of energy flow from the unstable modes to large coherent structures through the inverse cascade process and, if it exists, the process of energy flow directly into the mode structures.

Fluctuations have been detected in various SMT devices [1]–[17], [20]–[25]. The interpretations of these fluctuations and their implications have varied according to what was termed the most significant result from a particular device. For example, it was thought that SMTs mimic the characteristics of fluctuations in the scrape-off layer (SOL) of fusion devices [11]–[16]. Consequently, there is great support for the idea that SOL physics can be learnt from these devices with greater ease, simply because plasma is accessible for diagnostics with simpler probes. Some researchers have viewed these devices as laboratory experiments for studying various phenomena occurring in space plasma [20]–[22]. Fascinating as they are for the reason that SMTs lack MHD equilibrium, a larger picture has also been built around it based on important contributions made by fluctuations to the stability of the plasma via fluctuation-induced anomalous plasma transport, cross-field current systems and $E \times B$ plasma drift.

Greiner et al [7] have attempted to obtain a unified view of assigned differences between the results and conclusions from various SMT devices to the energy source of plasma production and not to the specific device parameters. They note that while the time-averaged profiles and the discharge mechanisms are found to be severely different for the plasma sources due to thermionic emission of primary ionizing electrons and RF power, the characteristics of obtained fluctuations and large-scale coherent structures are surprisingly similar. They do not depend on the discharge type. Encouraged by the revelation of signatures of mode structure in their
fluctuation data and, specifically, that large-scale structures are not stochastic, they suspect that all SMTs are pervaded by mode structures rather than coherent structures produced by the inverse cascade. The operation parameter space of these devices, specifically a toroidal magnetic field of $\geq 0.1$ T, is such that a large component of fluctuations is broadband, resembling plasma turbulence.

We deliberately operated BETA in a magnetic field of $\sim 0.02$ T, a value just above the threshold of exciting instabilities. In this mode of operation, fluctuations are dominated by coherent modes. The observed conditionally averaged spatio-temporal structure of this coherent mode is similar to what defines a large coherent structure due to the inverse cascading process. However, the appearance of frequency and wave vector peaks in the power spectrum [25] and long time auto-correlations (figure 7) identify these spatio-temporal structures as mode structures. The structures as observed in the poloidal cross-section of BETA device propagate along the $E \times B$ direction. We summarize that differing plasma characteristics are imposed upon the mode structure during its evolution. Consequently, a mode structure undergoes morphological changes in the parameters of its definition. When only the edge of these structures touches the limiter, they keep on growing, indicating that the ingestion of plasma is greater than the loss due to diffusion to the limiter. After a while, part of these structures is scraped off; however, the remainder keeps on rotating in the poloidal direction along with the background flow. The structures keep on going around in the poloidal cross-section till a large part of the structure hits the limiter. At this point of time, the structure starts decaying, which leads to the final demise of the structure. Importantly, what appears to be a perpetual periodicity dominated time series actually consists of a series of spatio-temporal structures having a definite life cycle of secular growth and decay phases. Additionally, mode structures last about two poloidal rotations before they disappear.

Here we make the conjecture that turbulence can evolve a large mode structure through processes of mode–mode coupling due to global variation of free energy sources. The coherent mode structure never attains a stationary state and is always undergoing secular changes in its morphological characteristics over the time scale of hundreds of microseconds. In principle, the growth rate of the unstable modes, approximately a few $\mu$s, is so fast that it could quickly reach a saturation state and/or nonlinear state. This implies that the stability of the structure may depend on the global profile of plasma parameters, not only on local parameters and their gradients.

An interesting proposal we make here is that BETA possesses a dynamic equilibrium in which plasma oscillates between two non-equilibrium states. There is a dynamic relationship between the free energy stored in the gradients of plasma parameters, plasma density, potential and temperature, and the plasma transport, which is largely a modified free fall of plasma. The vertical polarization electrostatic field set up by gradients and curvature in the toroidal magnetic field is reduced but not completely neutralized by either radial electric-field-induced poloidal drift or the limiter. This residual electric field causes free fall of the plasma with the reduced value of $E \times B$ advection. During the advection time from the center to the vessel boundaries, the plasma may poloidally rotate, lasting about the observed circulation time of two rotations of density blobs, which is observed as a large fluctuation. In this scenario, the observed large fluctuation is interpreted as plasma advection. When plasma is lost to the walls, the external energy source stores free energy once again in the source to start another cycle of dynamic interaction. These serially repeated dynamic cycles appear as oscillations in the time series and as perpetually growing and decaying spatio-temporal structures.
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