# First results of the Gas Puffing Imaging Diagnostics
# in a reversed-field pinch plasma

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The results of the gas-puffing-imaging (GPI) technique, obtained for the first time in a reversed-field pinch (RFP) plasma, are presented. GPI is a technique for diagnosing turbulence in edge plasmas by optically observing the line intensity emitted from gas puffed into the plasma. GPI is particularly suitable for high-temperature plasmas under severe heat flux, such as thermonuclear fusion plasmas, compared with the conventional probe method. A complex GPI (CGPI) system, which consists of GPI and a rake probe, has been developed [1], and used in the toroidal pinch experiment RFP device, TPE-RX [2]. We report that the optical signals obtained from the CGPI system indicate an intermittent nature of turbulence, and show a toroidal propagation of fluctuations of 20-30 km/s, and that the basic nature of the fluctuations is consistent with that simultaneously measured with the rake probe.

GPI was originally applied to tokamak plasmas [3, 4], and turbulence structure and dynamics in scrape-off layer (SOL) plasmas were reported. Recent results in ALCATOR CMOD [4] have shown the propagation of a 'blob' structure in the SOL. In RFPs, there have been extensive studies on edge turbulence using electrostatic probes [5-7]. Two important observations have recently been reported. The intermittent nature of the edge plasmas in the reversed-field pinch experiments RFX [5] in Padua and T2R [6] in Stockholm was identified by analyzing the probability distribution function (PDF) of floating potential fluctuations at different time scales, measured using electrostatic probes. A two-dimensional reconstruction of the $\boldsymbol{E \times B}$ flow in the edge of RFX [7] showed the presence of coherent structures emerging from the background turbulence in the edge. Whether these properties are common to all RFP plasmas, and similar to those of turbulence in different magnetic confinement systems at several plasma parameter regimes, remains as an open question. GPI is a suitable technique to address these issues since it is a noninvasive diagnostic technique, which can be easily used in different experiments. For this purpose, a CGPI system has recently been developed as a collaboration between Consorzio RFX and AIST, to be installed first in TPE-RX and then in RFX. This is the first report of the physics results obtained using the CGPI system in TPE-RX.

The GPI portion of the CGPI consists of a gas-puffing and optical systems to collect the plasma radiation, with a pair of parallel mirrors leading to the sets of lenses, optical fibres,

interference filters for $H_\alpha$ line (also applicable to $D_\alpha$ line) emission, which are lastly connected to two 16-channel photomultiplier tubes. The optical system is focused onto a viewing area 70 mm (toroidal) ✕ 4 mm (poloidal) ✕ 40 mm (radial) with a spatial resolution of 5 mm. The rake probe with 2 ✕ 6 pins and an additional pin at the top is also installed in the CGPI, and the probe can be inserted in the SOL and edge plasma on a shot-by-shot basis using a stepping motor. The floating potential $V_f$ is measured from each pin, and electron temperature and density can be measured using the three top pins as a triple probe. Only $V_f$ measurements are described in the present paper. 45 signals are acquired in total using a stand-alone data acquisition system of DC-8 MHz bandwidth with a sampling time of 100 ns and 4 MWord of 12-bit resolution per channel. The fast sampling with a sufficient record length that covers the whole discharge duration is necessary for the study of plasma turbulence. More details of the CGPI can be found in ref. 1. The CGPI was mounted at the top port of the TPE-RX vacuum vessel. TPE-RX has major ($R$) and minor ($a$) radii of 1.72 m and 0.45 m, respectively. TPE-RX is characterized by an all-metal first wall, which leads to relatively high $I/N$ values ($\sim 10 ✕ 10^{-14}$ Am), where $N = \pi a^2 <n_e>$ and $<n_e>$ is the volume-averaged electron density. The experiments with the CGPI were conducted under several sets of experimental conditions, where the plasma current $I_p$ was varied from 250 kA to 350 kA with pinch parameters $\Theta$ of 1.5 and 1.7. Deuterium gas is used for the main plasma as well as for the puffed gas in the CGPI.

Figure 1 shows typical waveforms of $I_p$, loop voltage $V_l$, reversal parameter $F$, line-averaged electron density $n_{el}$, and the line intensity of $D_\alpha$, $I_{D\alpha}$, at the central channel (#7) of the main optical array viewing the toroidal profile, when the gas is puffed. The piezoelectric valve for gas puffing is triggered typically 50 ms before the $I_p$ start and kept open for 80 ms so that the puffed gas forms a cloud during the discharge. This is confirmed using the CCD camera with an interference filter for the $D_\alpha$ line, which was attached at the bottom port of the same poloidal section of the CGPI location. The total amount of gas flux and the cloud density supplied are estimated to be $10^{18}$ atoms/s and $3 ✕ 10^{17}$ m$^{-3}$, respectively. It is confirmed that gas puffing does not affect the global behavior of $n_{el}$ ($\sim 5 ✕ 10^{18}$ m$^{-3}$) as seen in Fig. 1. Note that bursts of fluctuations appear conspicuously on $I_{D\alpha}$ when gas is puffed. These fluctuations are
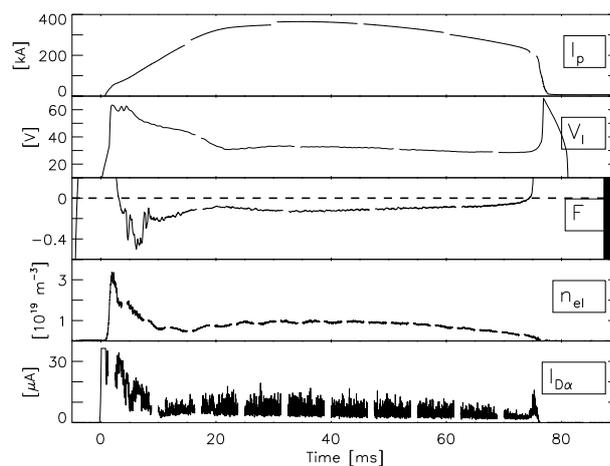


Fig. 1. Waveforms of $I_p$, $V_l$, $F$, $n_{el}$ and $I_{D\alpha}$ of central chord in CGPI system when deuterium gas is puffed.

predominantly linked to those of $n_e$ [8, 9].

The power spectrum of $I_{D\alpha}$ when gas is puffed shows the power law $S \sim f^{-3}$ for $f = 80$ kHz – 300 kHz and the power law $S \sim f^{-2}$ for without gas puffing. The total effective bandwidth of the optical system of the CGPI is measured to be 400 kHz. The stronger spectrum decay with gas puffing indicates that the fluctuations of $I_{D\alpha}$ have a local nature. Note that $I_{D\alpha}$ with gas puffing reflects the local turbulence information because $I_{D\alpha}$ from the puffed cloud dominates the signal, while $I_{D\alpha}$ without gas puffing gives line-integrated information about the background $D_\alpha$ and the local turbulence is smoothed out. When the rake probe is inserted into the edge of the plasma ($r \approx a$), the power spectra of the radial and toroidal electric fields, $E_r$ and $E_\phi$, respectively, are somewhat different from that of $I_{D\alpha}$ but a similar power law holds for $f = 300$ kHz – 1 MHz, where $E_r$ and $E_\phi$ are obtained from the differences in the $V_f$ values of the rake probe in the radial and toroidal directions, respectively, assuming $T_e$ is constant. It is confirmed that the insertion of the rake probe does not affect the power spectrum of $I_{D\alpha}$.

The power law decay of the power spectrum represents a qualitative indication of an energy exchange process between fluctuations at different scales. To detect the intermittent nature of this process, the PDFs of the $I_{D\alpha}$ fluctuations were analyzed as already done in RFX and T2R experiments. Indeed in a pure self-similar situation the PDF of the normalized fluctuations $\delta Y_\tau / \sigma_\tau$ calculated at different time scales must collapse to a unique PDF, where $\delta Y_\tau$ is the $I_{D\alpha}$ fluctuations at the time scale $\tau$, evaluated by the wavelet transform method described in [10], and $\sigma_\tau$ is the standard deviation. Intermittency is responsible for the breaking of this self-similarity with an increase in the tail of the PDF at smaller scales.

To quantify the breaking of self-similarity, the PDF of $I_{D\alpha}$ fluctuations at different $\tau$ values and the scaling properties of the flatness $F(\tau)$ have been evaluated. The flatness is the fourth order moment of the PDF, and qualifies the weight of the tails with respect to the core of the distribution. For the GPI signals, $F(\tau)$ increases for small time scales,
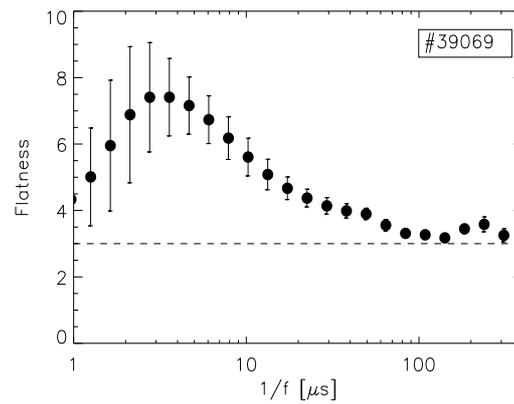


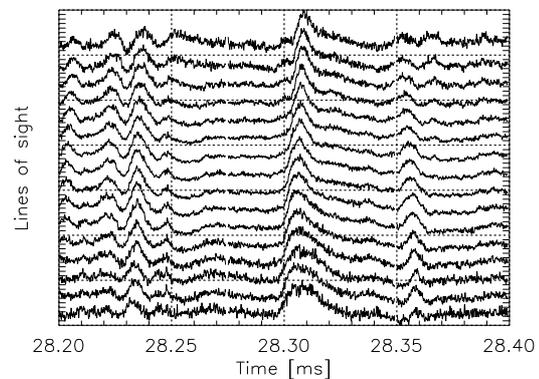Fig. 2. Flatness of $I_{D\alpha}$ fluctuations as function of time scale $1/f$.



Fig. 3. Typical fluctuations of arrayed $I_{D\alpha}$ signals in CGPI for shot number 39069.

assuming non Gaussian values (F > 3) when $\tau < 100$ μs (Fig. 2). Thus, the appearance of the intermittent nature seems to be commonly observed in RFP plasmas [5, 6, 11].

Also found is a toroidal propagation of fluctuations. Figure 3 shows temporally expanded fluctuations in $I_{D\alpha}$ in the 16 central chords. The chords are aligned in the toroidal direction, and a propagation of a burst is distinctly seen at $t \approx 28.3$ ms. The cross-correlation among the channels yields an average propagating velocity of 20-30 km/s in the direction opposite to that of $I_p$. The average correlation length is estimated to be 0.2-0.6 m. The dispersion relation between $f$ and the wave number $k$ (Fig. 4) is approximately linear in the region $f = 0$-80 kHz and $|k| = 0$-20 m$^{-1}$. The average trend yields $2\pi f/|k| \sim 20$-30 km/s, which is consistent with the toroidal propagation of fluctuations in Fig. 3.

The GPI experiment has been successfully conducted for the first time in the RFP TPE-RX. The result shows consistency with the electrostatic probe method, proving the usefulness of the GPI technique for thermonuclear fusion plasmas. The results obtained concerning turbulence in the edge of TPE-RX reveal an intermittent nature of fluctuations, and toroidal propagation at 20-30 km/s.

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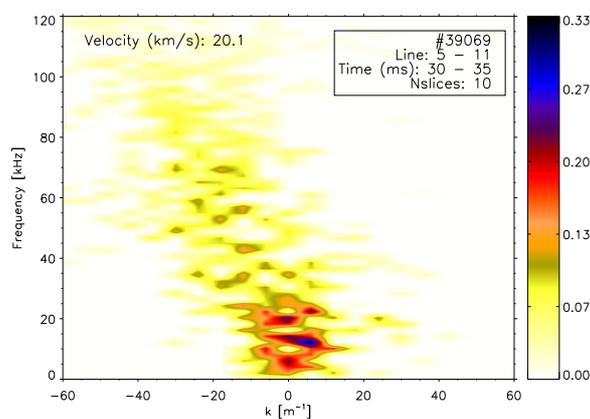
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Fig. 4. Dispersion relation of arrayed $I_{D\alpha}$ signals in the CGPI.