**Turbulent Transport and Coherent Structure Dynamics in Non-Stabilized Plasma at the Edge of the GOLEM Tokamak**

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**Abstract**

Plasma turbulent transport is investigated at the edge of the GOLEM tokamak. In particular, measurements of ion saturation current fluctuations are performed by means of Langmuir probe. Plasma stabilization was not activated during discharges under study. Non-Gaussian behavior indicates the presence of coherent structures. Study of the radial dependence of statistical and temporal characteristics of fluctuations allows to conclude that non-elongated blob-like structures with comparable radial and poloidal size should govern the plasma transport at the edge of the GOLEM tokamak.

Keywords: Controlled Thermonuclear Fusion, Fusion Plasma, Tokamak, Plasma Turbulent Transport, Coherent Structures, Intermittent Bursts

**Introduction**

Investigation of plasma turbulent transport processes is an important part of fusion research. The reason is that turbulent transport reduces confinement. At the same time it can cause strong erosion and high heat load on plasma facing components together with unwanted retention of tritium in next generation devices like ITER [1]. Turbulent transport has bursty and intermittent character. Coherent turbulent structures are responsible for such behavior [2]. These structures are formed on diffusive background, plasma density and temperature inside them are higher compared to those in background plasma. They propagate mostly radially with the speed which is fraction of ion sound speed. Langmuir probes are one of the most common diagnostics used for investigation of plasma turbulent transport [2-6]. During propagation of coherent turbulent structure radially outwards when they pass the Langmuir probe pin we detect the burst in temporal evolution of plasma density. Generally, bursty plasma transport is quite universal phenomenon and was detected in various fusion devices like tokamaks [7-14], stellarators [15, 16], linear devices [2, 12, 17-19], reversed field pinches [20, 21] and simple magnetized toroidal devices [22, 23].

We study statistical and temporal characteristics of plasma turbulent fluctuations together with their radial dependence for better understanding of plasma turbulent transport processes.

**Experimental set-up**

GOLEM is small size tokamak. It was known as CASTOR tokamak and operated at the Institute of Plasma Physics, Academy of Sciences of Czech Republic, Prague for 30 years [24]. After that it was transferred to the Faculty of Nuclear Physics and Physical Engineering, Czech Technical University in Prague and renamed GOLEM [25].

Major radius of GOLEM tokamak R = 0.4 m, minor radius r = 0.1 m. Stainless steel discharge chamber is equipped with poloidal limiter which is made of molybdenum and has the radius of a = 0.085 m. Maximum toroidal magnetic field is 0.5 T, central electron temperature is less than 100 eV, maximum line average density ~1019 cm-3 and discharge duration up to 25ms.

In order to investigate plasma turbulent transport in GOLEM tokamak dedicated experiments have been performed. Namely, ion saturation current (*Isat*) was measured by means of double rake probe inserted into the discharge chamber from the bottom diagnostics port. The rake probe consists of 12 Langmuir probe pins. There are two radial columns with 6 pins in each column. Two columns are poloidally separated by 2.5 mm. Radial distance between the probe pins in each column is also 2.5 mm. Sampling frequency is 1 MHz. 8 discharges were performed in order to make radial scan of edge plasma – the probe radial position changed from shot to shot. In this paper we present the results calculated from the data obtained on the left pin closest to the nose of the radial rake probe, because this data is most unperturbed by probe shaft.



***Fig. 1*** *Temporal evolution of toroidal magnetic field for 8 discharges under study*

Each discharge lasted for about 25 ms. *Isat* measurement continues during whole discharge. Since plasma current and toroidal magnetic field in GOLEM tokamak increase during discharge (see the Fig.1 and Fig.2), we analyze the data from 1 ms long time window after 15 ms. At this stage of discharge toroidal magnetic field and plasma current nearly reach their maximum values (around 0.45 T and 6 kA respectively) and do not change significantly (see the Fig.1 and Fig.2). Therefore, confinement should be high and machine functioning in most tokamak-like regime, namely flat-top phase of tokamak discharge.



***Fig. 2*** *Temporal evolution of plasma current for 8 discharges under study*

Generally, GOLEM discharges are well reproducible. Good reproducibility of discharges is confirmed by temporal evolution of loop voltage (see Fig. 3).



***Fig. 3*** *Temporal evolution of loop voltage for 8 discharges under study*

During discharges under study plasma stabilization was not activated. For this reason plasma column moves inside discharge chamber (see the Fig.4).



***Fig. 4*** *Plasma position in the discharge chamber of GOLEM tokamak during typical discharge*

During 1 ms time window after 15 ms from the beginning of discharge plasma occupies only small part of discharge chamber and has contact with poloidal limiter on its upper part on high field side, which is shown in the Fig.5. The same figure demonstrates, once again, good reproducibility of the discharges in GOLEM tokamak. It should be also mentioned that our measurements are generally performed in the SOL (scrape-off layer). Namely, first pin of the left column on the rake probe (closest to the nose of the probe shaft), the results from which we present in this paper, is always outside the last closed flux surface (LCFS) and its radial position changes within r = 45÷80 mm range.



***Fig. 5*** *Plasma position in the discharge chamber of GOLEM tokamak in 15-6 ms time window for the discharges under study*

**Experimental Results**

Our study of the physical nature of plasma turbulent transport at the edge of GOLEM tokamak involves statistical analysis as a first step. Radial dependence of *Isat* skewness is presented on Fig. 6. We see that *Isat* skewness is positive and generally increases radially. Positive skewness of plasma fluctuations and generally non-Gaussian behavior is quite common at the edge of tokamaks [2-6]. Positive skewness indicates presence of coherent turbulent structures in tokamak edge plasma which propagate radially outwards. We have explained this by physical picture described in [26-30]. Coherent structures are localized in poloidal plane and are elongated along the magnetic field line (mainly in toroidal direction). Plasma density and temperature inside them are higher than ambient plasma density and temperature. Coherent structures propagate radially outwards as a result of electric drift due to presence of poloidal electric and toroidal magnetic fields.



***Fig. 6*** *Radial profile of Isat skewness*

When coherent structures propagate radially outwards plasma density and temperature inside them decrease due to parallel losses (along the magnetic field line) and also deformation-spreading in poloidal plane. At the same time plasma density and temperature inside coherent structure decrease slower compared to ambient plasma mean density and temperature (which also decrease radially outwards) respectively. Therefore, during radial propagation plasma density and temperature inside coherent structures become increasingly higher compared to the same mean quantities for ambient plasma and when they pass the probe pin this gives rise to increasingly high amplitude positive *Isat* fluctuation (burst) and positive skewness. Thus, as the radial distance increases skewness increases too. This is what we observe in GOLEM – *Isat* skewness generally increases radially outwards (see the Fig. 6).



***Fig. 7*** *Radial profile of Isat average burst rate*

For better understanding of plasma turbulent transport and coherent structure dynamics at the edge of tokamaks together with statistical characteristics we have successfully used study of the radial dependence of *Isat* fluctuation temporal characteristics such as burst rate, inter-burst time and burst duration [26-30]. Bursts are selected using threshold method. Here we use threshold of one standard deviation. Radial evolution of *Isat* average burst rate at the edge of the GOLEM tokamak is presented on Fig. 7.

We see that generally average burst rate decreases radially. The reason for radial decrease of average burst rate is that during radial propagation coherent structures decay as a result of parallel losses (along the magnetic field line) and also deformation-spreading in poloidal plane. At the same time coherent structures have distribution in size – number of structures is decreasing function of their size. It is evident that larger structures propagate further and reach the radially distant regions. Thus, as radial distance increases less number of coherent structures reach this region and average burst rate decreases [26-30].

Radial profile of *Isat* average burst duration is presented on Fig. 8. Average burst duration increases radially. This happens due to deceleration of coherent structures during radial propagation and also their deformation-spreading in poloidal plane – coherent structure becomes larger in poloidal plane and moves slower. Consequently, as the radial distance increases more time is necessary for coherent structures to cross the probe pin and average burst duration increases [26-30].



***Fig. 8*** *Radial profile of Isat average burst duration*

**Discussion**

When we investigated plasma turbulent transport at the edge of CASTOR tokamak, we observed similar radial dependence of statistical and temporal characteristics of *Isat* fluctuations [29]. Namely, skewness increased, average burst rate decreased and average burst duration increased in radial direction. But these radial profiles were much flatter compared to the same radial profiles from GOLEM tokamak [29]. The reason is that radially elongated coherent structured – streamers governed plasma turbulent transport in the CASTOR tokamak [29, 31]. Formation of radially elongated structures was possible in the CASTOR tokamak due to high content of neutrals in edge plasma and high collisionality of plasma particles with neutrals [31]. Collisions dump zonal flows [32] and formation of radially elongated structures - streamers becomes possible. In the paper [29] we performed comparative analysis of fluctuation statistical and temporal characteristics of CASTOR and Tore Supra tokamak. In case of Tore Supra tokamak these characteristics changed significantly in radial direction and profiles were not nearly flat like on CASTOR tokamak. In the framework of physical picture proposed by us it is evident, that when radial elongated streamer-like structures govern plasma radial transport, radial profiles of statistical and temporal characteristics will be nearly flat. But, if plasma transport is governed by blob-like structures with comparable poloidal and radial size, in such case statistical and temporal characteristics of fluctuations will change significantly in radial direction.

We observe significant modification of statistical and temporal characteristics of plasma turbulent fluctuations at the edge of GOLEM tokamak. Based on physical picture presented in the previous section it is evident that non-elongated – blob-like structures with comparable poloidal and radial size should be governing radial transport at the edge of GOLEM tokamak.

The reason why blobs and not streamers are formed at the edge plasma of GOLEM tokamak should be the following. Plasma temperature in GOLEM tokamak is much lower compared to the CASTOR tokamak. At the same time plasma column is much smaller in cross-section compared to the discharge chamber (in case of the CASTOR tokamak plasma column feels entire poloidal cross-section) and has small contact region with poloidal limiter mostly on upper high field side (see the figures 4 and 5). For these reasons less neutrals are extracted from limiter and their content in the plasma of GOLEM tokamak should be much less compared to the CASTOR tokamak. Therefore, collisionality in GOLEM plasma should be low. Due to this zonal flows are not damped in the GOLEM tokamak and they do not allow formation of radially elongated structures – streamers. Therefore, we have more blob-like structures at the edge of the GOLEM tokamak.

**Conclusion**

We investigated turbulent transport of non-stabilized plasma at the edge of the GOLEM tokamak. Study of the radial dependence of *Isat* fluctuation statistical and temporal characteristics together with comparison with the results obtained during similar investigations preformed on the CASTOR tokamak allowed to conclude that non-elongated – blob-like structured with comparable poloidal and radial size should govern plasma turbulent transport at the edge of GOLEM tokamak.

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We dedicate this paper to the honored memory of our colleague Dr. Jan Stöckel, who was the initiator of investigations in the field of plasma turbulent transport on CASTOR and GOLEM tokamaks.

**Statements and Declarations**

V. Svoboda supervised the work. All the other authors equally contributed to the work.

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