Study of the ELM-free regimes by Doppler backscattering in the Globus-M tokamak

A.Yu. Yashin[1], V.V. Bulanin[1], V.K. Gusev[2], G.S. Kurskiev[2], V.B. Minaev[2], M.I. Patrov[2], A.V. Petrov[1], Yu.V. Petrov[2], A.M. Ponomarenko[1]

[1]*Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia*

[2]*Ioffe Institute, St. Petersburg, Russia*

In this paper we present the results of study plasma rotation velocity and plasma density fluctuations in regimes with improved confinement characterized by the absence of edge localized modes (ELMs). Two events were investigated: the transition from ELM to ELM-free H-mode and I-phase. These two phenomena are united by the appearance of quasi-coherent (QC) fluctuations. QC fluctuations have been observed through a spectral analysis of plasma density fluctuations derived from the Doppler backscattering (DBS) diagnostics. The four-frequency DBS scheme was utilised. Microwave beams at frequencies of 20, 29, 39 and 48 GHz were simultaneously launched into the plasma at angle to the flux surface. The perpendicular rotation velocity $V_\perp$ of plasma fluctuations can be estimated from Doppler frequency shift of the backscattered radiation. The intensity of the backscattering fluctuations in the selected k-band can be evaluated as well.

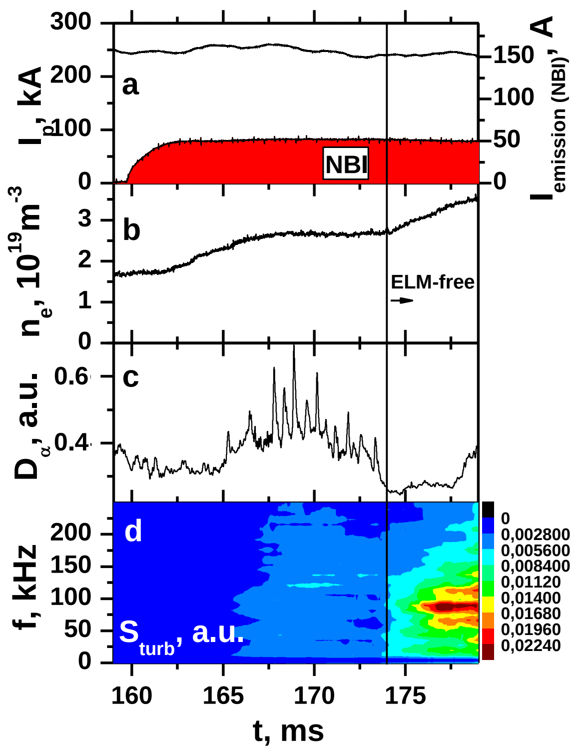

Figure 1. Time evolutions of a) plasma current and neutral beam emission current, b) central line-integrated electron density, c) D_α light emission, d) Spectrogram of DBS amplitude (probing frequency F = 48 GHz , ρ = 0.56 wavenumber of scattering fluctuations $k_\perp$ = 7.6 cm-1). Vertical line denotes the transition to the transient ELM-free H-mode. #36701

ELM-free H-mode. In the regime with a plasma current of 240 kA and a magnetic field of 0.5 T, a relatively late launch of NBI at 160 ms was carried out at the stationary stage of the plasma current. Figure 1 depicts the temporal evolution of selected parameters for Globus-M H-mode discharge with NBI.

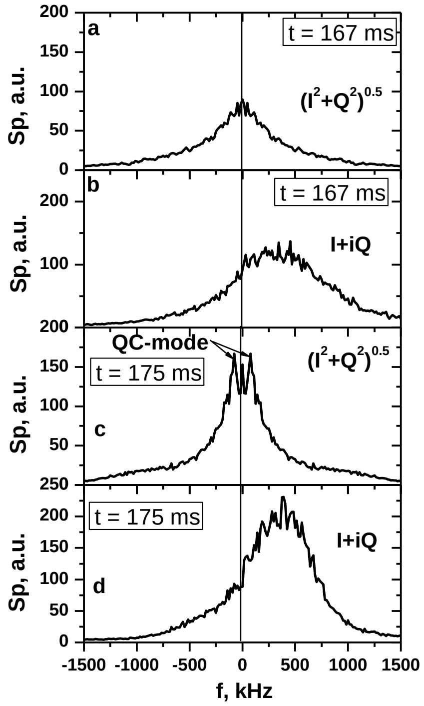

Figure 2. Power spectra before the transition to the transient ELM-free H-mode. Time – 167 ms. a) spectrum of DBS amplitude b) spectrum of IQ complex signal. Power spectra after the transition. Time – 175 ms. c) spectrum of DBS amplitude d) spectrum of IQ complex signal. Probing frequency F = 48 GHz . #36701

The transition to H-mode occurs a few milliseconds after the beginning of the beam injection (this is typical for the Globus-M tokamak [1]) and accompanied by ELMs that can be seen as periodical D_α bursts. The existence of ELMs stops the increase of plasma density. The disappearance of these ELMs at 174 ms leads to improvement of particle confinement. D_α drops and plasma density starts to increase simultaneously. This mode lasted a relatively short time, since it was limited by the duration of the discharge itself. During this ELM-free H-mode [2], quasi-coherent (QC) fluctuations were found in the form of oscillations in turbulence amplitude at the frequency f_{QC} = 80 kHz with a wide spectrum Δf_{QC} = 100 kHz (Figure 1d) only on the highest frequency (48 GHz) channel, when the cutoff radius ρ = 0.6. It is noteworthy that at large radii ρ = 0.7- 0.9 QC was not observed , moreover, the level of broadband turbulence in the periphery region fell by 15 - 20% compared with the level of turbulence before switching to ELM-free regime. Figure 2 depicts the comparison of two turbulence amplitude spectra. The first spectrum corresponds to the H-mode with ELMs (Figure 2a). This spectrum is typical for this regime. Its maximum is located near the zero frequency. The value of the spectrum amplitude decreases with the turbulence frequency increase. But in the case of ELM-free H-mode one can see the local maximum near f_{QC} (Figure 2c). Symmetric spectra of the real signals are presented solely for the purpose of having the same frequency scales as those for the complex IQ signals (See Figure 2 b and d). Each spectrum shown is the result of averaging 30 spectra calculated from samples of signals with a duration of 64 μs; the total analysis time is 1.9 ms, the frequency resolution is 15.6 kHz. By using the frequency shift $\Delta\omega_D$ of the complex IQ signal spectra, the average plasma velocity in the diamagnetic direction was calculated according to the relation $\Delta\omega_D = k_\perp V_\perp$. The complex IQ signal spectra broadening is due to several reasons. First of all, backscattering occurs on plasma density fluctuations with $k_\perp$ lying in the range determined by the $k_\perp$-spectrum resolution of the method [3]. Secondly, broadening occurs due to the velocity shear in the scattering volume near the cutoff, which in our case is limited by a radial resolution of about 1 cm. Finally, broadening is possible due to fluctuations of the velocities of the plasma perturbations. However, it seems worthy of note that there are no frequency peaks in the spectra of the complex IQ signal in the event that we are able to detect the QC fluctuations in the amplitude of backscattered radiation spectra. This, apparently, indicates that the wavenumber the QC fluctuations is outside the range of the method resolution.

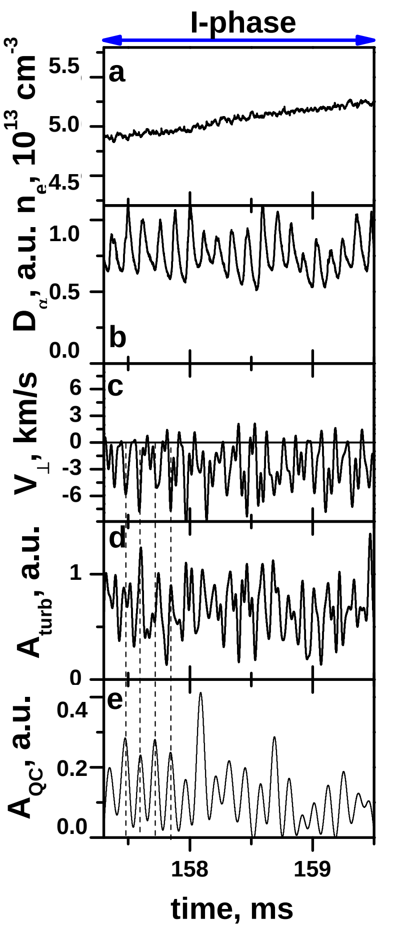

Figure 3. Time evolutions of a) line-integrated electron density, b) D_α light emission, c) perpendicular plasma rotation velocity, d) DBS amplitude, e) DBS amplitude filtered in frequency band of QC fluctuations (f_{QC} ± 40 kHz). #37000

I-phase

Similar QC fluctuations were also found in the I-phase [4]. The I-phase was achieved in a discharge with a plasma current of 200 kA, a magnetic field of 0.5 T and NBI started at 130 ms. The I-phase in Globus-M is characterized by limit-cycle oscillations (LCO) which are detected as D_α emission signal, perpendicular rotation velocity or radial electric field (~ E_r), intensity of backscattering fluctuations (turbulence) oscillations and magnetic field oscillations at frequency 5-8 kHz (see Figure 3.b-d) [5]. QC fluctuations during the I-phase were detected in the DBS amplitude. The frequency of QC fluctuations was found to be f_{QC} = 110 kHz with a turbulence amplitude spectrum width Δf_{QC} = 80 kHz.

A more detailed look at the QC fluctuations showed that their amplitude was regulated by LCO. In Figure 3.e, one can see that the amplitude of QC fluctuations oscillates similarly to LCO. The amplitude reaches its maximum when the plasma rotation velocity approaches its maximum value. When the rotation velocity is close to zero, the QC fluctuations disappear.

In order to determine the nature of the instability responsible for the development of QC fluctuations, calculations were performed in the linear local approximation using the gyrokinetic code GENE. The calculations predict two types of instabilities: the micro tearing mode (MTM) and ITG. MTMs are mostly responsible for electron heat transport and hardly contribute in particle transport. However, the electron temperature profile does not change during the time of existence of the QC fluctuations (Figure 4-T).

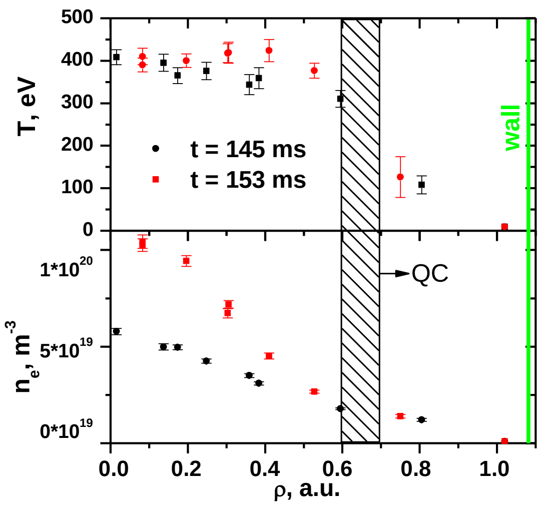

Figure 4. Radial profiles of electron temperature (top) and density (bottom) in the L-mode (t=145 ms) and in the I-phase (t = 153 ms). #37000

An increase in the density gradient was observed at radii ρ < 0.6 (Figure 4-n_e). Moreover, the density profile shows plateau formation in the region of occurrence of the QC fluctuations in I phase. ASTRA 7 transport code simulations demonstrate the increase in a diffusion coefficient inside this area. This increase in diffusion and flattening of the density profile may be related to the development of the ITG mode. Therefore we assume that the QC fluctuations are caused by the ITG instability. MTM can be suppressed as a result of nonlinear interaction of ITG and MTM [6], and the ITG mode is dominant and is responsible for a large flux of particles.

Conclusions. Quasi-coherent fluctuations in the ELM-free H-mode appeared and increased with a frequency of $f_{QC} \approx 100$ kHz in the frequency band near $\Delta f_{QC} \approx 50$ kHz in the inner region ρ = 0.6. The frequency of QC fluctuations in the I-phase was found f_{QC} = 110 kHz with a spectrum width Δf_{QC} = 80 kHz. The experiments have shown that the QC fluctuations are localized in the ρ = 0.6 – 0.7 region. QC fluctuations amplitude is modulated by LCO. They appear when the plasma velocity increase and disappear when it decrease. The QC fluctuations develop in the same area that the plasma density profile flattens. As simulations with the use of the ASTRA 7 transport code showed the location corresponds to increased diffusion coefficient value. GENE simulations predict both ITG and MTM in the location of QC fluctuations revealing. We assume that in our case QC fluctuations are the result of the development of the ITG.

Acknowledgements. This work was executed with the financial support of the Russian Science Foundation, grant # 18-72-10028

[1] Gusev V.K. et al 2011 Nucl. Fusion 51 103019
[2] Yashin, A.Y et al. Plasma Phys. Rep. 46, 683–688 (2020)
[3] Bulanin V.V. and Yafanov M.V. 2006 Plasma Physics Reports Vol. 32, No. 1, pp. 47–55
[4] Schmitz L. et al 2017 Nucl. Fusion 57 025003
[5] Yashin A.Yu. et al 2018 Nucl. Fusion 58 112009
[6] Doerk H. et al Phys. Plasmas 22, 042503 (2015)