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Analysis of toroidal Alfven eigenmode-induced fast ion losses in Globus-M2 spherical tokamak

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With an increase of magnetic field up to 0.8 T and plasma current to 400 kA, fast ion losses rate in the discharges with toroidal Alfven eigenmodes decreased in tokamak Globus-M2 comparing with Globus-M tokamak discharges. Taking into account the data on the discharges with increased magnetic field and plasma current, the regression fit of neutral particle analyzer flux drop in energy channel close to neutral beam energy on relative eigenmode magnitude, the value of magnetic field and plasma current was analyzed. The power of flux drop dependence on TAE magnitude was found to be ~ 0.5 and inverse proportional on the value of product of magnetic field and plasma current, which is highly likely is determined only by plasma current due to weak dependence on magnetic field. The result obtained indicates that fast ion losses in Globus-M2, stimulated by toroidal Alfven eigenmodes are mostly determined by the shift of passing orbits to the plasma edge. With the increase of plasma current and magnetic field, neutron flux drops arising in the moments of toroidal mode bursts have also decreased.

Keywords: TAE, NPA, spherical tokamak, fast ion losses

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Introduction

Toroidal Alfven eigenmodes (TAEs) are able to affect fast particle confinement in tokamaks, as their excitation occurs due to the resonance with suprathermal ions with velocities comparable with Alfven velocity $\upsilon_A = B_0/\sqrt{\mu_0\rho_i}$ (B_0 — unperturbed magnetic field, ρ_i — mass density of plasma ions, μ_0 — vacuum magnetic permeability). Resonance condition is satisfied for ions with velocities close to υ_A and $\upsilon_A/3$ [1,2]. The energy source for TAE excitation, as a rule, are high energy ions produced due to charge-exchange reactions between bulk plasma and the neutral beam (NBI) or radiofrequency heated ions (ICRH) [2,3]. It is also reported about TAE excitation in regimes with electron-cyclotron resonant heating (ECRH) [4]. TAE were frequently observed in plasmas of the most of spherical tokamaks MAST [5], NSTX [6], START [7], Globus-M [8,9], since the aspect ratio of a tokamak is one of the basic parameters that affect the width of the frequency gap, so the gap is wider for spherical tokamaks than for traditional ones [10]. Alfven eigenmodes have a significant effect on the neutron yield not only because they can lead to the final losses of fast particles, but also since they lead to the redistribution of fast particles both in the velocity space and in physical space. The transfer of fast particles to peripheral regions with a lower temperature and density, firstly, can reduce the slowing down time of fast ions, and secondly, it directly leads to a decrease in the neutron yield due to a decrease in the number of reactions at low density. In traditional tokamaks, toroidal Alfven eigenmodes pose danger from the point of view of fast ion losses: the losses associated with TAE modes can reach 70% of all ions injected into the plasma [3]. For spherical tokamaks, losses associated directly with TAEs are less studied. In [11] a decrease in the neutron yield up to 15% after so-called Alfven avalanche in NSTX tokamak is reported, and 25% decrease in neutron yield during fishbone instability, arising just after TAE mode in MAST tokamak, was reported in [12]. Losses associated directly with single TAE bursts in spherical tokamak require particular consideration. It is especially important to study the effect of TAE on the fast ion confinement precisely in the context of a fusion neutron source based on a spherical tokamak, which operation should be provided in a quasi-continuous regime, with a predominant portion of plasma current driven by non-inductive methods (neutral injection, radio-frequency current drive). A significant part of the neutron yield of a neutron source should be due to the interaction of fast ions formed due to injection of a neutral beam with thermal plasma and with each other. Toroidal eigenmodes can also influence the energy balance in future reactor-type devices (ITER [3]), where thermonuclear alpha particles are responsible for maintaining the reaction, which, having slowed down sufficiently, are also able to lose their energy in resonance with the Alfven wave. At the same time, the issue of predicting the amount of fast ion losses caused by toroidal Alfven eigenmodes seems to the authors to be developed quite weakly and requires additional analysis. To study such dependences, two approaches are frequently applied, which are numerical codes (for example, the ASCOT [13] code is used to analyze the interaction of Alfven modes with particles), and the construction of scalings or regression fits based on a large number of experimental data. Each of these approaches has its own number of advantages and disadvantages. This work is devoted to obtain a linear regression for the charge exchange atom analyzer (NPA) flux drops.

Section 1 describes the design of the Globus-M2 tokamak and its diagnostic complex applied in the experiments on TAE observation. In Section 2, a regression fit is obtained for the fast ion losses on TAE magnitude and plasma parameters. Section 3 is devoted to the influence of Alfven modes on the neutron yield.

1. The experiment on Globus-M2 tokamak

Globus-M2 is a compact spherical tokamak (major radius $R = 36$ cm, minor radius $r = 24$ cm, aspect ratio $A = 1.5$) [14, 15], which is an upgraded version of Globus-M tokamak [15,16]. The tokamak is equipped with two [17,18] high energy neutral beam injectors of 1 MW power each, first one designed for 30 keV and another for 50 keV neutral beam energy. Tokamak diagnostic complex is also equipped with two neutral particle analyzers (NPA) ACORD-12 and ACORD-24M [19]. Each one is intended to detect both hydrogen and deuterium atoms with temporal resolution of 0.1 ms. ACORD-12 has six energy channels to detect hydrogen atoms (each channel can be adjusted in range of 250 eV$-$30 keV), and six deuterium channels for energies varying in range of 400 eV$-$20 keV. The analyzer is installed in equatorial plane normal to central column. ACORD-24M, in turn, has 12 hydrogen and 12 deuterium channels, adjustable in range of 250 eV$-$35 keV. This NPA is installed tangentially, with impact parameter equal to the first NBI impact parameter (30 cm). Neutron flux is being registered by means of ${}^{10}_{5}B$ coronal neutron counter remoted 12.5 meters from a tokamak and a by distant neutron spectrometer based on BC-501A [20] liquid scintillator. To register Alfven oscillations, a set of 8 magnetic probes is applied. Probes are located along the toroidal turn of a tokamak at equal angular distances from each other, measuring the radial component of the magnetic flux. The layout of the neutral beam injectors and elements of the diagnostic complex of the Globus-M2 setup is shown in Fig. 1.

In the experiments at Globus-M2 [9,21,22], where toroidal Alfven eigenmodes were found to arise during neutral beam injection, the first NBI with energy $E_{\mathrm{NBI}} = 28$ keV and beam power P_{beam} about 0.85 MW was applied. ACORD-24M NPA was used to measure neutral flux and ACORD-12 analyzer was applied to measure ion temperature [23]. Single TAE bursts, observed on magnetic probe signal caused short-time drawdowns in NPA channel, set up to register neutrals with energy close to the energy of neutral beam (28.5 ± 1.5 keV). Measurements of the value of the flux drops were provided with temporal averaging in 300 μs window. It should be noted that the drawdowns in NPA channel do not directly indicate the final loss of these particles, but only their redistribution from phase space region, observed by NPA. However, since such

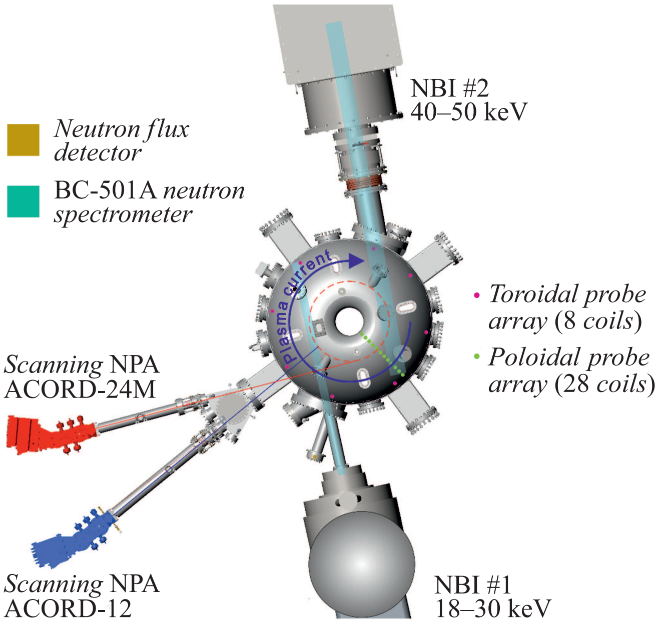

Figure 1. The setup of neutral beam injectors and diagnostics applied in TAE experiments.

flux drops are also observed on neutron detector signal, such a redistribution leads to a decrease in the neutron yield, which is especially important for a fusion neutron source. Toroidal Alfven eigenmodes on Globus-M tokamak were being registered in wide range of plasma parameters $\langle n_e \rangle < 10^{20}\,\mathrm{m}^{-3}$, $I_p = 180-250$ kA, $B_T = 0.4-0.5$ T both at the current ramp up and plateau stage [9]. On the Globus-M2 tokamak the values of magnetic field of $B_T = 0.6-0.8$ T and plasma current up to 400 kA were achieved, that made one possible to analyze the dependence of fast ion losses in a wider range of plasma parameters and to complete [24] the results obtained earlier [21,22] with new experimental data (Fig. 5 in paper [21], Fig. 1 in [24]). Experimental data points corresponding to higher values of magnetic field and plasma current, as it was considered earlier, lay in the figure much lower than points that correspond to lower values of magnetic field and current, which indicates the decrease in fast ion losses. Moreover, the behavior of the data points for, corresponding to low values of magnetic field (0.4$-$0.5 T) and current (0.18$-$0.25 MA), tends to saturation for relatively high mode magnitudes ($>$ 4 Gauss). However, there is no saturation found for higher values of magnetic field (0.6$-$0.8 T) and plasma current (0.3$-$0.4 MA). Points, that correspond to saturation region, were excluded from further analysis.

2. Fast ion loss analysis

The regression fit of relative flux drops of NPA signal on TAE magnitude — δB, toroidal magnetic field B_0 and plasma current I_p was being looked for in the form of $dN/N = C\delta B^{\alpha} B_0^{\beta} I_p^{\gamma}$, where C is free parameter. The value

Pearson correlation coefficients ρ_{xy} between δB, magnetic field and plasma current

	δB	B	I_p
δB	1	0.25	0.36
B	0.26	1	0.52
I_p	0.36	0.52	1

of flux drop of the analyzer signal is $dN/N = (N_1 - N_2)/N_1$, where N_1 and N_2 — the number of NPA counts before and after TAE burst respectively. Since with an increase in the magnetic field, plasma current increased proportionally in order to preserve the MHD stability in most of discharges, these quantities are not independent and have a large correlation (Pearson's correlation $\rho_{\beta\gamma} = cov(B_0, I_p)/\sigma(B_0)\sigma(I_p) = 0.64$). In Globus-M2 tokamak discharges with toroidal field $B_0 = 0.6-0.8$ T and current $I_p = 0.3-0.4$ MA, toroidal Alfven eigenmodes have become to arise predominantly at the current ramp up stage after mode transformation from Alfven cascades [25], that appear due to safety factor $q(r)$ reversal caused by skin effect at the current ramp up. Taking such specific TAE bursts into account followed in a decrease in Pearson's correlation between magnetic field and plasma current to $\rho_{\beta\gamma} = 0.51$, since at the current ramp up stage TAEs are able to arise in a wide range of plasma currents at fixed value of magnetic field. However, this consideration still does not allow us to use these values independently. Thus, parameter $B_0 I_p$ was used for further analysis, instead of separate variables. Also, in order to make it possible to compare the amplitudes of TAE bursts arising in tokamaks with different values of magnetic field (despite that such a comparison was not carried out), the dimensionless parameter $\delta B/B_0$ was used. Pearson correlation coefficients for three parameters are provided in Table. Thus, resulting regression fit was being looked for in form: $dN/N = C(\delta B/B_0)^{\alpha}(B_0 I_p)^{\beta}$.

Then, using least squares method, powers α, β and free parameter C and dispersions σ_α, σ_β were determined. Single measurements of the NPA flux drop were considered of unequal accuracy, distributed according to Poisson distribution with dispersions σ_i. Residual sum of squares χ^2 was minimized:

$$\chi^2 = \sum_{i=1}^{N} g_i \left(\ln\left(\frac{dN}{N}\right)_i - \ln C - \alpha \left(\frac{\delta B}{B}\right)_i - \beta (B_0 I_p)_i \right)^2. \quad (1)$$

Weightning coefficients $g_i = \sigma^2/\sigma_i^2$ were provided to take into account uneqal accuracy of single measurements, where quantity $\sigma^2 = 1/\Sigma\, 1/\sigma_i^2$ was determined from normalization condition of g_i coefficients to unity. Dispersions of single measurements were determined as:

$$\sigma_i = \frac{\sqrt{(N_{1,i} - N_{2,i})}}{N_{1,i}}. \quad (2)$$

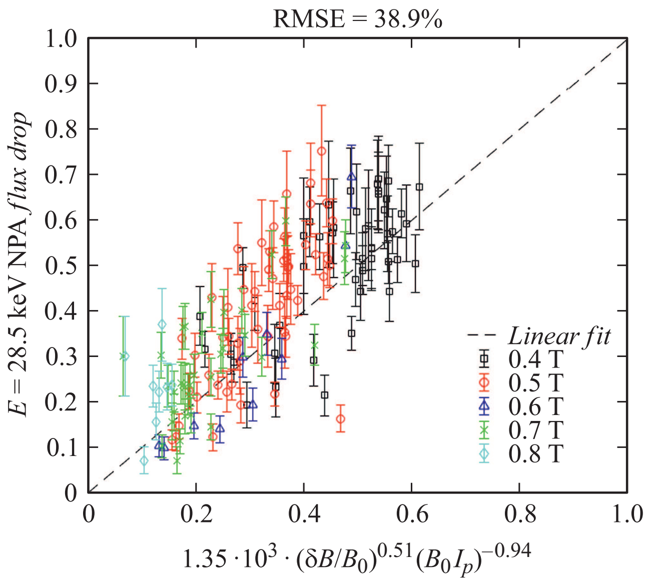

Figure 2. Regression fit of NPA flux drawdowns on relative TAE amplitude and a product of magnetic field and plasma current.

Dispersions of powers σ_α and σ_β were determined by calculation of covariation matrix for previously found estimations of coefficients $\bar{\alpha}$ and $\bar{\beta}$:

$$\begin{pmatrix} \sigma_\alpha^2 & cov(\alpha,\beta) \\ cov(\beta,\alpha) & \sigma_\beta^2 \end{pmatrix} = 2 \begin{pmatrix} \frac{\partial^2\chi^2}{\partial\alpha^2} & \frac{\partial^2\chi^2}{\partial\alpha\partial\beta} \\ \frac{\partial^2\chi^2}{\partial\beta\partial\alpha} & \frac{\partial^2\chi^2}{\partial\alpha^2} \end{pmatrix}_{\substack{\alpha=\bar{\alpha} \\ \beta=\bar{\beta}}}. \quad (3)$$

The resulting linear regression fit for NPA flux drops dN/N is given by equation:

$$\frac{dN}{N} = 1.35 \cdot 10^3 \left(\frac{\delta B}{B_0}\right)^{0.51\pm0.15} [B_0 I_p]^{-0.94\pm0.27}. \quad (4)$$

The errors provided in power indexes correspond to confidence interval with a given value of 3σ. The obtained regression fit is also presented in Fig. 2. It should be noted that each member of relation (4) is separate composite parameter, which parts should not be considered as independent variables, that was shown in the beginning of this section.

However, since the dependence between δB and B_0 is not rather high (see Table), The dependence of the value dN/N on unnormalized mode magnitude δB was provided in analogous way with fixed values of magnetic field and plasma current for three groups of experimental data points, presented in Fig. 2, which are: 0.4 ± 0.02 T and 200 ± 20 kA, 0.5 ± 0.02 T and 240 ± 20 kA, 0.6 ± 0.02 T and 300 ± 20 kA. For higher values of magnetic field and plasma current, TAEs with large amplitudes do not arise, therefore, the data for fields $0.7-0.8$ T and currents up to 400 kA were not presented in provided analysis. Power indexes found for the regression (Fig. 3) of NPA flux drops on δB fell into the confidence interval of parameter α, found for the dependence of dN/N on normalized mode

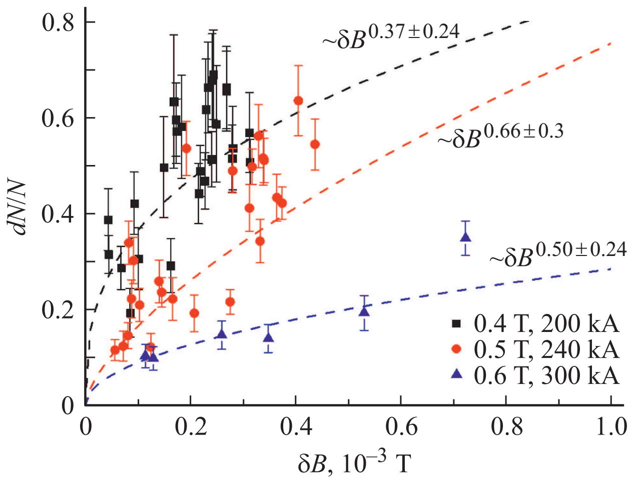

Figure 3. The dependence of NPA flux drops on TAE amplitude for three different values of magnetic field and plasma current at similar value of safety factor.

magnitude $\delta B/B_0$ in regression (4). From the provided speculation, one can conclude that power index in the dependence of dN/N on TAE magnitude δB close to 0.5 and the dependence on magnetic field is weaker. Thus, parameter $\delta = -0.94$, which is a degree of the dependence of the flux drop on the product $B_0 I_p$ (if not to take into account weak dependence on magnetic field) in equation (4) evidence that fast ion losses are mostly determined by the displacement of passing orbits along the major radius. The displacement of passing orbit from magnetic surface (in drift approximation) could be estimated as $d = R - R_c \sim q\rho_{ci} \sim 1/I_p$, where R is major radius of the orbit drift center, R_c — radius of the magnetic surface, where resonant fast ion was ionized, ρ_{ci} — ion Larmor radius, $q = q_{cyl}$ — safety factor in cylinder. Therefore, with the regression (4) one could conclude that the reduction of fast ion losses in Globus-M (M2) tokamak is predominantly determined by an increase of plasma current, as it was assumed in [9].

3. Influence of Alfven eigenmodes on the neutron yield

In discharges with Alfven eigenmodes, not only drawdowns in NPA signal were observed, but also a direct decrease in the neutron yield during TAE flares. The Globus-M2 tokamak has recently achieved magnetic field values up to 0.85 T and plasma currents up to 400 kA. This increase in plasma current and magnetic field has also affected the neutron yield. Earlier, for the Globus-M tokamak, the dependence of the number of detected neutrons on the TAE amplitude was obtained [22] for toroidal magnetic field of 0.4 T and plasma currents in the range of 180–230 kA based on the data of ^3_2He proportional neutron counter, which was previously used at the Globus-M tokamak. Due to the fact that neutron diagnostic has been upgraded (instead of a proportional counter, a coronal counter and a neutron spectrometer are now in use), it is almost impossible to compare new and previously obtained data. However, in experiments on the Globus-M2 device at magnetic field of 0.5 T and a current of 200–250 kA, TAE excitation have also caused short-term drawdowns in the neutron detector signal. In Fig. 4 signals of Mirnov coils (above) and temporal evolution of the number of neutrons detected in whole energy range of neutron spectrometer (below) are presented for three discharges: #39001 (0.5 T, 209 kA), #39027 (0.6 T, 246 kA), #38385 (0.7 T, 340 kA), where TAE bursts were registered with quasi-similar magnitude (about 10 Gauss). If there is about 30% drawdown in relative value of neutron flux drop found for the first two discharges, then for discharge #38385 this value is about 7%. It turns out that such small drawdowns could be hard to resolve on the background of fluctuations of the neutron detector signal. That imposes some limitations on the application of neutron diagnostics to analyze the losses of fast ions associated with the propagation of TAE.

4. Results and conclusion

The dependence of fast ion losses on TAE magnitude and plasma parameters was analyzed in this paper. Due to high correlation between magnetic field and plasma current the regression fit of NPA flux drop on relative TAE magnitude $\delta B/B_0$ and product $B_0 I_p$ was obtained. It was shown that the power index of the dependence on $\delta B/B_0$ is close to 0.5 and close to -1 on the parameter $B_0 I_p$. It was also shown that the dependence on B_0 is weaker, than on δB and plasma current. At the same time, it turned out to be rather difficult to separate the dependence on the magnetic field and on the plasma current, since most of the discharges of the Globus-M tokamak, provided at low values of toroidal magnetic field and plasma current, were provided with the safety factor being preserved, which followed in high correlation rate between these values. However, it is also incorrect to neglect the dependence on the magnetic field completely, since the explanation of plasma current dependence in terms of the drift orbit center displacement was obtained high aspect ratio approach and, of course, does not completely reflect the modification of drift orbits in a spherical tokamak. Nevertheless, the result obtained indicates that the basic reason for the decrease in fast ion losses in the Globus-M2 tokamak in comparison with Globus-M could be a reduction of passing orbits displacement from magnetic surfaces along major radius with increasing plasma current, as like as it takes place in classic tokamaks. Therefore, perturbations with comparable magnitudes no longer lead to the same losses due to particle expelling to the orbits where they are not confined. In order to separate the effect of plasma current and toroidal magnetic field on fast ion losses in Globus-M2 tokamak,

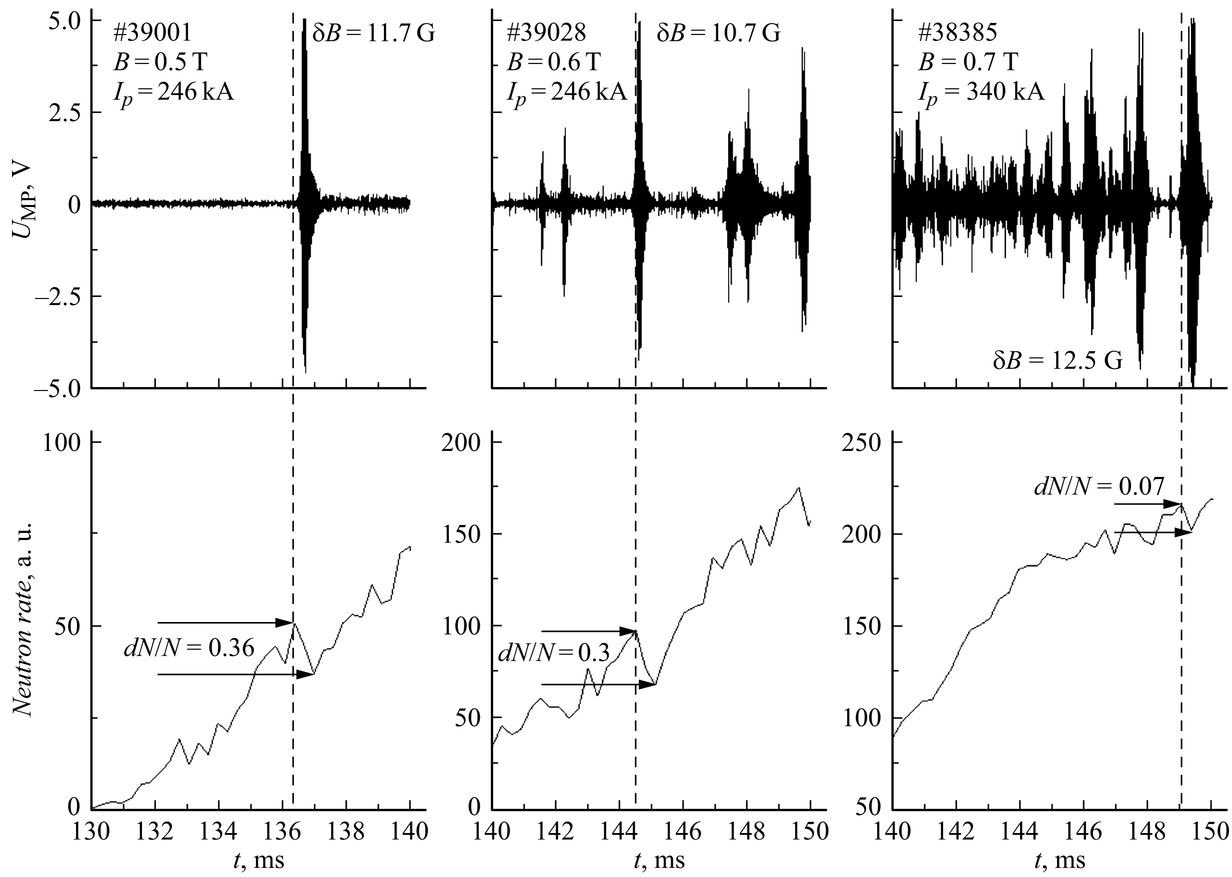

Figure 4. NPA signal drawdowns (below) caused by TAE bursts of quasi-similar magnitudes (MP signal — above) for three discharges with different values of magnetic field and plasma current. Left-to-right: discharge #39001 (0.5 T, 209 kA), discharge #39028 (0.6 T, 246 kA) and discharge #38385 (0.7 T, 340 kA).

a series of experiments on TAE observation providing scanning in a wide range of magnetic fields and currents are planned.

Further analysis by means of the method provided in this paper at higher values of magnetic field and plasma current (it is planned to increase toroidal magnetic field up to 1 T and plasma current to 0.5 MA) could turn out to be rather difficult, firstly, since TAEs does not lead to any sufficient losses anymore even at field and current values of 0.7 T, 300 kA (see Fig. 4), and secondly, there are sufficient changes being observed in TAE behavior at higher values of magnetic field and plasma current. In Globus-M2 tokamak TAE behavior follows predatr-prey model [9]. High instability growth rates cause a dramatic increase in mode amplitude, which follows in particle redistribution, and, in turn, rapid damping. In such a regime it is rather simple to identify NPA signal drawdowns during single TAE events. At higher values of magnetic field and plasma current, radial orbit displacement is lower, and TAE excitation does not follow in significant change of orbit radius. Therefore, since less of the resonant particles are being lost, the life time of single TAEs increases, their magnitude decreases, and no pronounced drawdowns in NPA signal are being observed. Essentially high value of standard deviation (38%) may evidence that there are a number of implicit dependences on other plasma parameters, and also on previous events, which caused the redistribution of fast particles in phase space.

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Conflict of interest

The authors declare that they have no conflict of interests.

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