STRUCTURE OF INTENSIVE MHD FLUCTUATIONS IN U-3M TORSATRON IN THE MODE OF LOW FREQUENCY COLLISIONS

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The structure of MHD-fluctuations in the frequency range 0.5…52 kHz of RF produced plasma was studied in the Uragan-3M torsatron by the use of magnetic probes placed in one of the poloidal cross-sections. Three types of fluctuations with specific spatial (3D) structures were observed. The first type: when the structure amplitude is changing slowly and the structure rotates as a whole with some frequency. The second type: the structure does not rotate but its amplitude is time varying. The third type is a combination of the first two types: the structure rotates and at the same time its amplitude fluctuates. The correlation was found between the level of fluctuations and the time dependence of plasma energy content before and after transition to regime of better confinement of plasma.

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INTRODUCTION

The results of studies of magnetic field fluctuations (MF) performed at different toroidal plasma magnetic traps stimulated theoretical studies in this field. Currently, it was predicted a great number of instabilities that may cause MF. Above all, these are drift-Alfven and drift-sound eigenmodes DAE and DSE [1] or Alfven eigenmodes AE [2]. Besides, it is possible to have excitation of geodesic acoustic mode GAM [3], beta-induced Alfven eigenmode BAE [4], global GAM (GGAM) [5], GAM-like modes induced by energetic particles GAM – EGAM [6], beta-induced Alfven-acoustic eigenmodes BAAE [7, 8], parametric instabilities related to the plasma heating [9], etc. It is also worth mentioning that heating methods affect essentially the excitation of drift waves [10].

From the listed above it is clear that characteristics of plasma instabilities in toroidal traps depend on many factors and their behavior is rather variable. Thus, the ways to study these instabilities is to obtain the best possible information (under given conditions) on the frequency range, spatial structure of instability, plasma parameters and methods of its heating.

One of the most convenient methods to diagnose plasma instabilities accompanied by MF in the confined volume is to register the MF in the area of plasma confinement using the set of magnetic probes. In this case, one can obtain information on frequency range and spatial structure of these instabilities. As a rule, the multi-channel system for registration of MF is rather chip and convenient in operation. The main disadvantage of such diagnostics is fundamental inability to determine the area of instability localization in the plasma volume. Therefore, it is necessary to use additional measurements by the use of other diagnostics.

The aim of this article is to obtain the information on instability of plasma produced by RF methods in the l=3 torsatron Uragan-3M (U-3M) device in conditions of low collisions between plasma particles. The timepoint selected for detail studies corresponds to the moment when amplitude of MF reaches the maximum values and the rate of energy content increase is minimal.

1. EXPERIMENTAL CONDITIONS

Studies at U-3M [11] were performed in RF heating mode [12]. For plasma production and heating a so-called frame antenna was used. The frequency of antennae operation was close to the ion cyclotron frequency $\omega \approx 0.8\omega_{ci}$, the working gas – hydrogen. According to theory, the main mechanism of plasma heating is Cherenkov damping on electron of the waves excited in plasma under conditions of Alfven resonance [13]. It is known that this method of energy transfer to plasma electrons contributes to distortion of the energy distribution functions and to occurrence of the conditions for instability excitation (especially under low collision frequencies). Besides, considering that waves excited in plasma have frequency close to the ion cyclotron frequency, an additional ion heating is possible with corresponding distortion of the ion distribution function.

When providing these measurements, the mode of low plasma density $\langle n_e\rangle \leq 2\cdot10^{18}$ m^{-3} with the maximum density at magnetic axes $n_e(0)\approx(3…4)\cdot10^{18}$ m^{-3} [14] was of interest. In this mode, the electron temperature (average over the cross section of the plasma column) and the ion temperature reached $T_e \leq 200$ eV and $T_i \leq 300$ eV [15], correspondingly. The effective charge number averaged over the cross section of the plasma column was $Z\approx1$ [15]. Magnetic field on geometric axis of plasma configuration is $B_0\approx0.72$ T. This mode is interesting because electrons and ions are in a “banana” regime, what was confirmed by registration of the so-called bootstrap current [16]. It is known that the future thermonuclear reactor will operate in similar mode and thus, our studies can be useful.

2. EXPERIMENTAL RESULTS

In one cross section of plasma column a set of 15 magnetic probes (coils) registered the poloidal component of magnetic field were installed at a radius b_{pr}=16.8 cm (Fig. 1). The coils with diameter 6 mm and length 16 mm were placed inside the electrostatic screen and have sensitivity NS=180 coils•cm^2 (N is a number of turns in the coil, S is the area of the coil cross-section). Each coil with the connection cable (length 20 m) allowed to register the variation of poloidal magnetic field with frequency up to 70 kHz. Signals from probes were integrated using 16-channel electron integrator. The constant of integration varied in the range of $\tau=5\cdot(10^{-8}\ldots10^{-5})$ s.

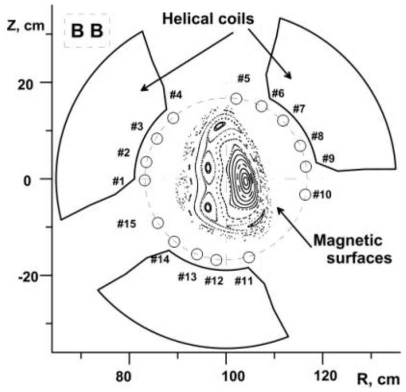

Fig. 1. The poloidal cross-section of the torus showing positions of helical coils, magnetic probes #1…15 and vacuum magnetic surfaces

The time interval, where the amplitude of fluctuation reaches maximal value $\tilde{B} \leq 0.3$ G, was selected for detail study of the structure of fluctuations in the plasma confinement volume. In this moment, an essential decrease of growth rate of plasma energy content was observed what was recorded by a diamagnetic loop (Fig. 2, upper curve). As seen, there is a rapid decrease of fluctuation amplitude at the end of the time interval studied (time moment 35.3 ms is indicated by the dotted line in Fig. 2) with corresponding increase of plasma energy content

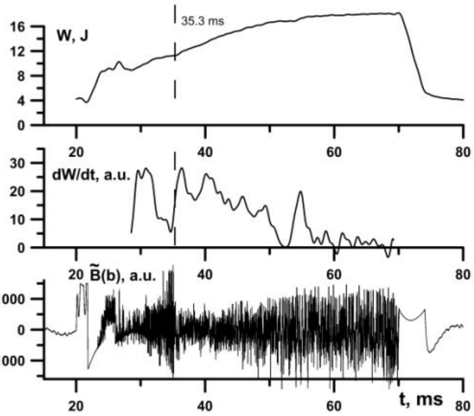

Fig. 2. Time behavior of the plasma energy and its derivative, and the signal from one probe (the lowest time profile). The dotted line shows the moment of a sharp rise of the plasma energy content

Fig. 2 shows that the recorded signals (the lowest oscillograms) are non-stationary and represent a set of consecutive fluctuation groups, where one or several oscillations with variable amplitudes and frequencies do occur. Since it is incorrect in such a case to speak about local frequency, we will use the term “frequency bandwidth”. Correspondingly, the obtained raw implementations were divided into 5 frequency ranges to process the obtained set of signals, such that: $\delta f_1=0.5\ldots5$ kHz, $\delta f_2=5\ldots11$ kHz, $\delta f_3=11\ldots20$ kHz, $\delta f_4=20\ldots31.5$ kHz, $\delta f_5=31.5\ldots52$ kHz. The sampled signals were then implemented in a certain frequency range by the use of band-pass filters. In this way the distributions of signal amplitudes along the whole set of probes were obtained for any given time moment for any of this frequency range. The obtained data were represented as a set of harmonics with various poloidal wave numbers m=0; 1; 2; 3 (Fig. 3,b). The higher harmonics with m>3 were not considered because the accuracy of their identification using 15 probes is rather small in conditions of the experiment. The amplitudes of this spatial harmonic were recorded for the measurement surface (b_{pr}=16.8 cm) together with their phase shifts relatively to the previous point in time. The knowledge of harmonic amplitudes on the measurement surface allows to recalculate the fluctuation amplitude for the radius within the confinement volume according to the formula described in [17]. As was shown in that paper, the decrease of the magnetic field for each poloidal harmonics is described by Bessel functions, which in the first approximation can be written as: $(b_{pr}/b)^{m+1}$, where m is the number of poloidal harmonics. The re-calculation was done for the radius b=8.4 cm (inside of confinement volume) with taking into account that the averaged radius of plasma column is $\langle a\rangle$=10 cm. It is obvious that there is a dramatic underestimation of the role of fluctuations with higher poloidal wave numbers in comparison with the level of fluctuations inside plasma column. Therefore below in the text, for the purpose of information objectivity, only those data re-calculated for the inside plasma volume will be further discussed.

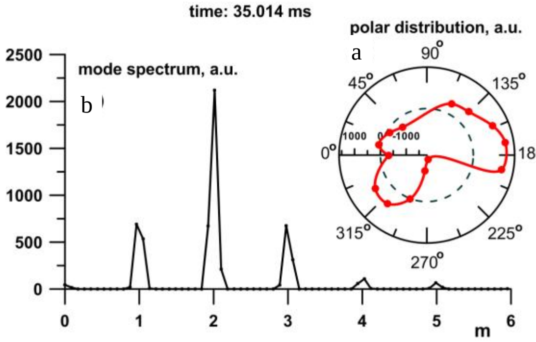

Fig. 3. Polar distribution of signals amplitude from the magnetic probes at the time point of 35.014 msec (a) and mode spectrum of this distribution along poloidal wave numbers (b)

The results of recorded signals processed are shown in Fig. 4 for the frequency range δf_2=5…11 kHz. In this figure, for each spatial harmonic the time variation of the phase of this structure φ (regarding external plane point of the facility) and its amplitude are shown. The amplitude is shown as $\tilde{B}^2$.

As it is clear from Fig. 4, the phase of the structure m=0 possesses the values “0” and “π” what corresponds to the sign change of the fluctuation amplitude. Based on the fluctuation period one can estimate the frequency bandwidth where the fluctuations are realized. For example, according to Fig. 4, in the time interval t=35.1…35.3 ms there is only one full fluctuation in the frequency range 6.5…7.3 kHz. From the physical point of view, the structure with m=0 can be either fluctuations of plasma current or fluctuations of the confining magnetic field.

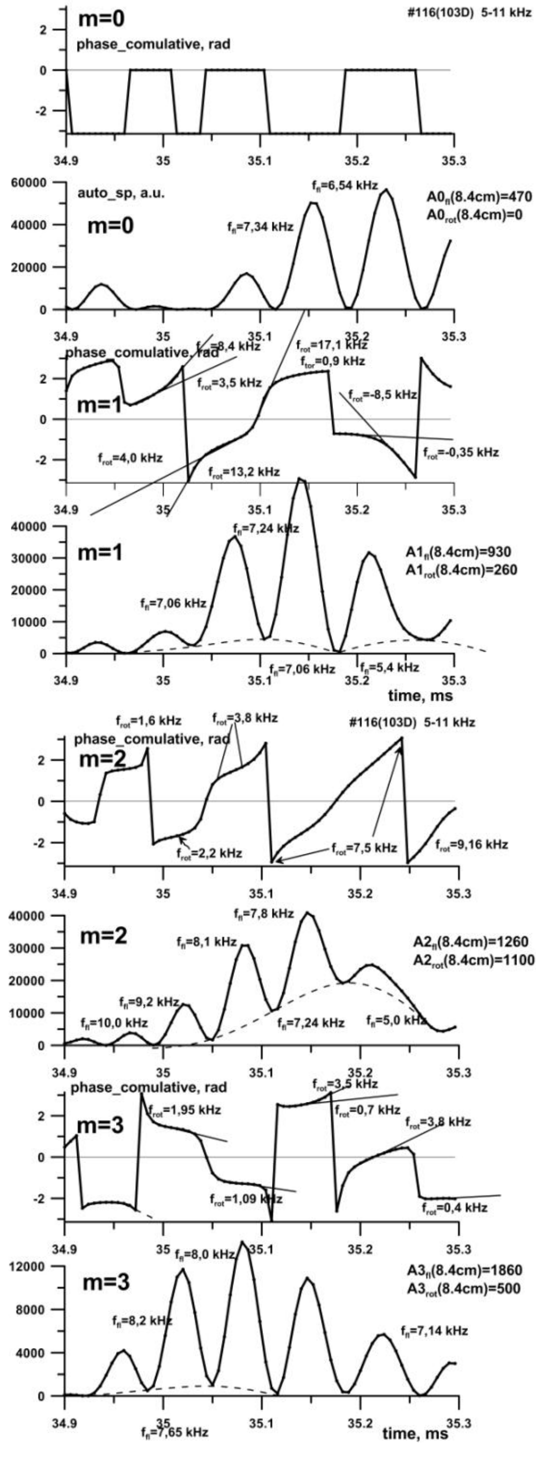

Fig. 4. Dependences of amplitude and phase in the frequency bandwidth of δf_2=5…11 kHz for poloidal wave numbers m=0; 1; 2; 3

By analyzing all available experimental data we conclude that there are three types of fluctuations registered in this experiment. The first one, when the structure with the given wave number is standing or slowly rotates; its amplitude changes with the recorded frequency. The fluctuations of this type are observed permanently. The second one is the structure rotating with a certain frequency and the amplitude slightly varying with time. Most often, its rotating velocity is not constant in time. Typically, the fluctuation frequency of the “standing on the spot” (SOS) structure is close to the rotating velocity of the second type structure. If we consider that SOS structure can quickly turn to a certain angle when its amplitude approaches zero, then it seems that this SOS structure stimulates the rotation. The third type is a combination of the first two types.

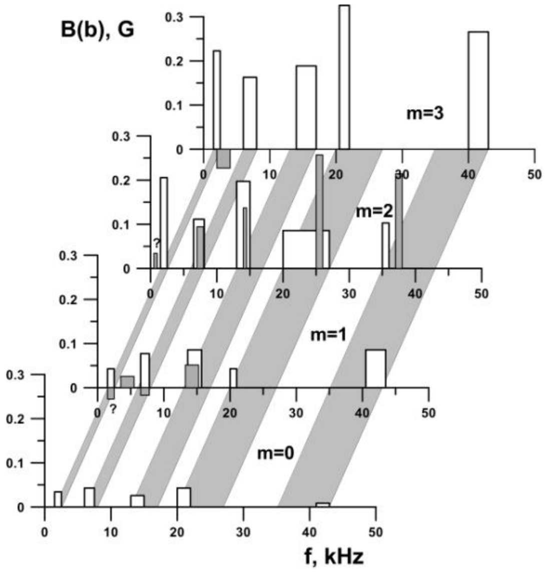

Fig. 5. Dependence on the recorded frequency bandwidth of the maximal amplitude module of fluctuations for spatial structures with different poloidal wave numbers m. The light bars determine the standing structures and the shaded bars show the rotating structure. The rotation direction towards electron rotation in the magnetic field is taken as positive

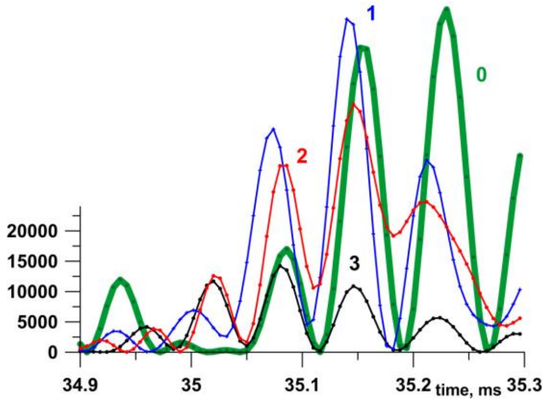

Fig. 6. Fluctuation amplitudes of four spatial structures with m=0; 1; 2; 3 in the frequency range of 6…8 kHz on the measurement surface

Fig. 5 shows the dependence on the recorded frequency bandwidth of the modules for maximum fluctuation amplitudes of spatial structures with m=0; 1; 2; 3. The positive and negative amplitude modules correspond to different directions of structure rotation (shaded bars). The positive values correspond to rotation in the direction of electron Larmor rotation. The light bars define the maximum amplitude of the SOS structure. The column width shows the approximate frequency range of the recorded fluctuations.

The analysis of experimental data shows that MF exists in a rather narrow frequency ranges that are common for spatial structures with different poloidal wave numbers. MF were recorded in the frequency ranges: 1.5…2 kHz, 6…8 kHz, 13…16 kHz, 20…27 kHz, 35…43 kHz (Fig. 5).

For structures with m=1 and m=2 there observed a rotation in different directions in the frequency range 1.5…2 kHz but we failed to determine the value of the rotating structure. The maximum values of MF of the SOS structures are observed for m=2 and 3.

In the frequency range 6…8 kHz there are fluctuations of both the SOS structures with m=0; 1; 2; 3 and the "rotating" structures with m=1; 2; 3 (see Fig. 4). It should be noted that all fluctuations of the SOS structures are interrelated. In other words, their frequencies and phases are close to each other and represent a common perturbation for all spatial structures (Fig. 6). The amplitude of fluctuations inside the plasma confinement volume increases with increasing the poloidal mode number (see Fig. 5). The structures with m=2 have the maximal amplitude of the rotating structure wherein the rotation rate increases with increasing the fluctuation amplitude of the SOS structure, and coincides with its frequency at maximal amplitude.

For the fluctuations in the range of 13…16 kHz the rotation is present only for the structures with m=1 and m=2. The SOS structures are correlated with each other (except for m=0) and have maximal amplitude for structures with m=2 and m=3. The amplitudes of the rotating structures are less than the amplitudes of the SOS structures.

Fluctuations of the SOS structures in the bandwidth of δf_4=20…31.5 kHz are in the range of 20…22 kHz except for the structure with m=2, the bandwidth of which is 20…27 kHz. Only the structure with m=2 rotates with the frequency f_{rot}=25…26 kHz, wherein the amplitude of the rotating structure exceeds essentially the amplitude of the SOS structure.

In the bandwidth δf_5=31.5…52 kHz the fluctuations of the SOS structures are in the range 40…43 kHz except for the structure with m=2 where there are fluctuations in the bandwidth 35…37 kHz and the rotation frequency is f_{rot}≈37 kHz. The amplitude of the "rotating" structure in the maximum is higher than of the SOS structures. The fluctuations of the SOS structure with m=3 have the maximum amplitude.

As can be seen from fig. 5, the rotation of the structures with m=1; 2; 3 for the frequency bandwidths δf_1=0.5..5 kHz and δf_2=5…11 kHz is taking place. The question marks in this figure indicate that the rotation of the structure is qualitatively seen, but the rotation amplitude cannot be identified. Also, it is clear that for m=1 and m=3 the frequencies of "rotating" structures differ essentially from the frequencies of the SOS structures. Probably we observe the initial stage of the structure rotation, which is breaking away for some reason, and does not reach the maximum of the frequency.

CONCLUSIONS

The performed studies showed that in the low collision frequency plasma produced by RF power in the torsatron U-3M the quite narrow-band fluctuations are arising in 5 frequency ranges: 1.5…2 kHz, 6…8 kHz, 13…16 kHz, 20…27 kHz, 35…43 kHz.

The spatial structure of these fluctuations is characterized by poloidal wave numbers m=0; 1; 2; 3.

There are three types of fluctuations:

- the standing or slow rotating structures, which amplitude changes within certain frequency range;
- the rotating structure which amplitude changes slightly and the maximum rotation frequency is close to the fluctuation frequency of a "standing" structure;
- the third type is a combination of the first two types: the structure rotates and at the same time its amplitude fluctuates.

The standing structures can represent a complex configuration (fluctuations with different wave numbers correlated with each other).

The rotating structures can have different poloidal numbers, however, their maximal amplitudes have structures with m=2. The direction of rotation of these structures coincides predominantly with the direction of electron Larmor rotation.

The standing structures have maximum fluctuation amplitude at the poloidal wave number m=3 and its magnitude is up to $\tilde{B}$ ≈0.3 G in the plasma confinement volume.

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СТРУКТУРА ИНТЕНСИВНЫХ МГД-ФЛУКТУАЦИЙ В ТОРСАТРОНЕ У-3М В РЕЖИМЕ РЕДКИХ СТОЛКНОВЕНИЙ

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С помощью набора магнитных датчиков, размещённых в одном из полоидальных сечений, на установке Ураган-3М исследовалась структура МГД-колебаний плазмы в диапазоне частот 0,5…52 кГц. Наблюдались 3 типа колебаний, имеющих определённую пространственную структуру. Первый тип колебаний, когда амплитуда почти не изменяется со временем, а их структура вращается с определённой частотой. Второй тип – пространственная структура не вращается, но её амплитуда изменяется в определённом диапазоне частот. Третий тип представляет собою объединение первых двух типов – структура вращается, и при этом наблюдаются колебания амплитуды. Была обнаружена связь уровня флуктуаций и временного поведения энергосодержания плазмы перед переходом в режим улучшенного удержания и после него.

СТРУКТУРА ІНТЕНСИВНИХ МГД-ФЛУКТУАЦІЙ В ТОРСАТРОНІ У-3М У РЕЖИМІ РІДКИХ ЗІТКНЕНЬ

В.К. Пашнєв, Е.Л. Сороковий, А.А. Петрушеня, Ф.І. Ожерельєв

За допомогою набору магнітних датчиків, розміщених в одному з полоідальних перетинів, на установці Ураган-3М досліджувалася структура МГД-коливань плазми в діапазоні частот 0,5…52 кГц. Спостерігалися 3 типи коливань, що мають певну просторову структуру. Перший тип коливань, коли амплітуда майже не змінюється з часом, а їх структура обертається з певною частотою. Другий тип – просторова структура не обертається, але її амплітуда змінюється в певному діапазоні частот. Третій тип являє собою поєднання перших двох типів – структура обертається, і при цьому спостерігаються коливання амплітуди. Був виявлений зв'язок рівня флуктуацій та тимчасової поведінки енергозмісту плазми перед переходом у режим покращеного утримання і після нього.