IDENTIFICATION OF HARMONICS OF RF FIELD, WHICH IS USED FOR PRODUCTION AND HEATING OF PLASMA IN THE TORSATRON "U-3M"

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Experimental and numerical methods were used to identify the harmonics of the RF field used for plasma production and heating in the torsatron "U-3M".
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Experiments were carried out on the plasma having an average density $n_e = 2{\cdot}10^{12}$ cm^{-3} and a confining magnetic field B_0 = 0.72 T. The plasma was produced and heated by the RF method with excitation of current of frequency $\omega = 0.8\omega_{Bi}$ [1] in one frame antenna. The antenna-radiated power was $P_{RF} \leq 200$ kW.

The U-3M magnetic system is located inside a vacuum chamber, about 70 m^3 in volume. It is made up of three helical coils. The RF antenna is arranged along one of the coils at approximately 1cm from the inner surface. The antenna has no screen, and the RF field radiated by it occupies the entire chamber. The brass waveguide systems of microwave reflectometers inside the chamber are in essence the stub antennas for RF field reception. One of them ends with a horn antenna 1 (X-wave) on the outside, somewhat below the plasma bunch. The other waveguide system ends with a horn antenna 2 (O-wave) situated on the inside, over the plasma bunch (Fig. 1).

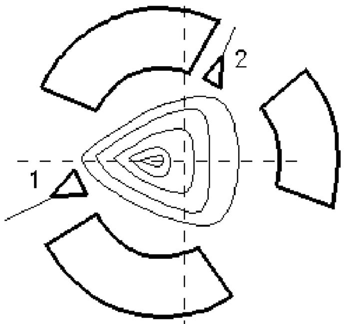

Fig.1. Shematic view of experiment (1, 2 — microwave antennas)

The HF currents induced in them penetrate the diagnostic room and thus come to the registering devices. In the analysis of LF signals from the reflectometers, the RF noise is easily filtered out. However, if the frequencies of useful signals and parasitic signals are comparable in value, their separation and identification become complicated [2]. The spurious signals of the HF field were taken from the reflectometer detectors in the regular way, but without the RF filters. Therefore, the signals to be analyzed represented the reflectometer signal proper, which carried the information on LF plasma-density fluctuations Δn_e , and the induced RF antenna currents.

The reflectometer signals were supplied to the ADC at the clock frequency f_{ADC} = 1428.57 kHz. The characteristic oscillograms of the discharge are shown in Fig. 2.

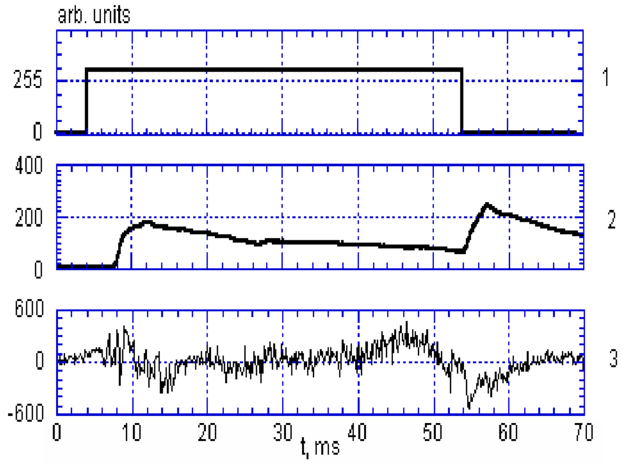

Fig.2. RF power (1), averaged electron density (2), summarize signal of UHF reflectometer (3)

The power spectral density (PSD) of one of the signals is shown in Fig. 3. Here three peaks with the frequencies f_1 = 194.8 kHz, f_2 = 389.6 kHz and f_3 = 584.4 kHz clearly stand out against the common level of fluctuations of Δn_e . From the peak values it follows that $f_2 = 2\,f_1$ and $f_3 = 3\,f_1$.

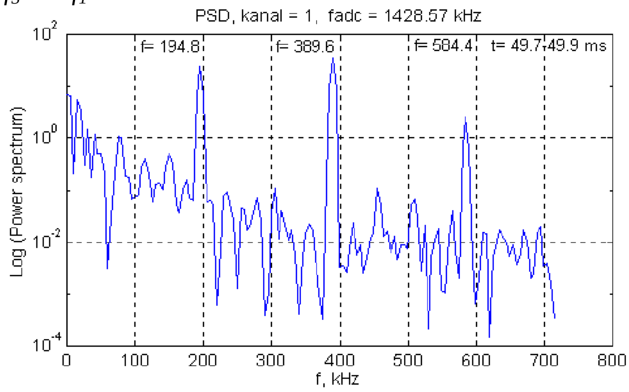

Fig.3. Spectrum of signal (X-wave, F = 19.1 GHz)

This means that the frequencies of the peaks are the harmonics of one source. To determine this source, the PSD was calculated for many successive windows over the course of one discharge (Fig. 4). The harmonics appear with the onset of the RF pulse (4 ms) and disappear with its end (54 ms). During the discharge the peak frequencies are somewhat displaced, however the frequency ratio is retained. The presence of peaks is independent of the electron density value (see Fig. 2). With a two-fold increase in the clock frequency of the ADC the occurrence of seven harmonics was observed.

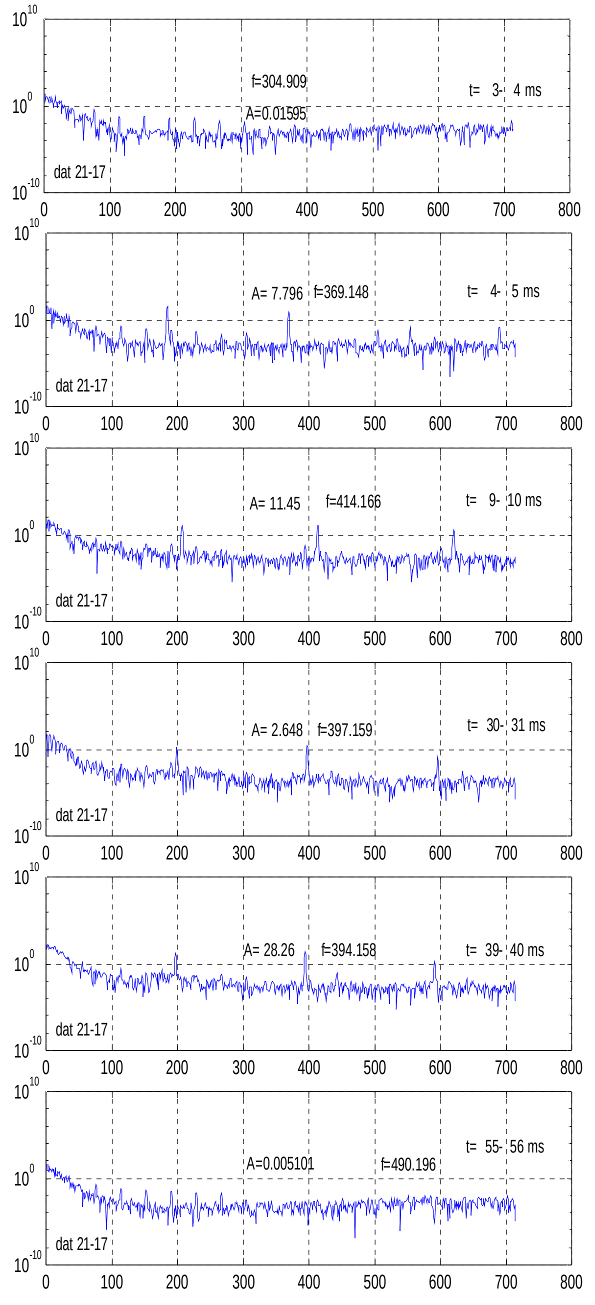

Fig.4. Spectra of signal (X-wave,F = 19.1 GHz)

In principle, the generation of electromagnetic wave harmonics is possible with the incidence of the pump wave on the inhomogeneous plasma [3]. The comparison between the conditions of excitation of electromagnetic-wave harmonics by the plasma and the conditions of their propagation [4] with the experimental data indicates that the external RF generator, the electromagnetic field of which is used in the U-3M for plasma production and heating, is the source of the harmonics observed.

However, the frequency of the first harmonic f_c observed is much lower than the fundamental frequency of the RF generator F_x. On the other hand, the frequency F_x is substantially higher than the clock frequency of the ADC used. For similar experimental conditions, the authors of ref. [2] have proposed a formula relating the RF signal frequency F_x to the frequency of “false” peaks f_c in the spectrum of signal under detection

$$F_X = n \cdot f_{ADC} \pm f_c , \quad (1)$$

where f_{ADC} is the clock frequency of the ADC, n = 1, 2, 3… To make use of the formula, it is necessary to find the n value and to determine the sign before f_x. To this end, the RF generator frequency was measured in the discharges under study by the independent method using the frequency meter. The f_c signals were registered at the same clock frequency f_{ADC} = 1428.57 kHz. For different ten fixed F_x values (the generator frequency could vary from discharge to discharge within ≈ 10 kHz) the corresponding f_c values were substituted, and through a gradual increase of n eq. (1) was solved. So it was established that formula (1) is fulfilled provided that n = 6 and f_c has the plus sign

$$F_X = 6 \cdot f_{ADC} + f_c . \quad (2)$$

Since in our case it is necessary to calculate not only the fundamental signal frequency but also the frequencies of signal harmonics, the formula can be generalized to have the following form:

$$F_{Xm} = m \cdot n \cdot f_{ADC} + f_c , \quad (3)$$

where m is the harmonic number, n = 6.

The calculations from formula (3) have proved that harmonics is PSD observed at frequencies f_1 = 194.8 kHz, f_2 = 389.6 kHz and f_3 = 584.4 kHz are traces of RF oscillator harmonics F_{x1} = 8766.22 kHz, F_{x2} = 17532.44 kHz and F_{x3} = 26298.66 kHz. Note that the harmonic frequencies are reproduced within of accuracy of to 1 kHz.

The model numerical experiment has confirmed this conclusion (Fig. 5). At the fundamental frequency of the RF generator F_{x1} = 8775 kHz the maximum of the spectrum is obtained at f_c = 203.68 kHz, and at the harmonics F_{x2} = 17550 kHz and F_{x3} = 26325 kHz the maxima of the spectra are found at f_c equal to 407.37 kHz and 611.04 kHz, respectively.

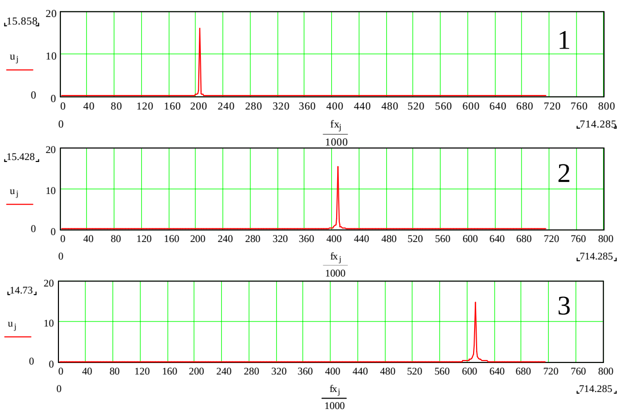

Fig.5. Spectra of signals model for: 1- f_1 = 8775 kHz, 2- f_2 = 17550 kHz, 3- f_3 = 26325 kHz

The excitation of harmonics means that if the generated oscillations substantially differ from the harmonic oscillations. Such systems are called the relaxation generators. Their generation spectrum is extremely wide. This is confirmed by a numerical model experiment. In Fig. 6, for the harmonic oscillation F_{x1} = 8775 kHz one peak in the PSD at f_c = 203.68 kHz is observed. If the oscillation is deviated from the harmonic oscillation by means of an arbitrarily chosen function, the spectrum shows the oscillations in the entire range registered up to 700 kHz (Fig. 6). The cause of generator oscillations deviation from the harmonic oscillations may lie in the formation of a space-charge layer with a nonlinear capacitance nearly the RF antenna [5]. This nonlinearity may disturb the resonance circuit of the RF energy input system.

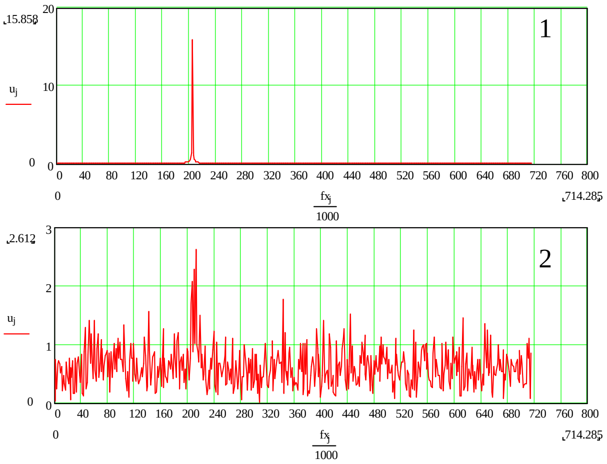

Fig.6. Spectra of signals model for f = 8775 kHz :
1 – A(t)=sin(ωt), 2 – A(t)=sin((ω+0.1·rnd(ω/100))·t)

To summarize, it may be noted the following. The observed electromagnetic-field harmonics are the harmonics of the HF field used for plasma production and heating in the torsatron “U-3M”. Numerical model experiments have confirmed the possibility of generating the harmonics by an external RF generator. It has also been demonstrated that spurious signals can be identified in the experiment if the ADC with a clock frequency substantially lower than the frequency of the signal under study is used in the registration system.

In future, it is supposed that variations in amplitudes and frequencies of RF field harmonics during the discharge will be investigated. The results to be obtained may be used for optimizing the operation of the RF generator as a source of plasma generation and heating in the torsatron “U-3M”.

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ИДЕНТИФИКАЦИЯ ГАРМОНИК ВЧ-ПОЛЯ, ИСПОЛЬЗУЕМОГО ДЛЯ СОЗДАНИЯ И НАГРЕВА ПЛАЗМЫ В ТОРСАТРОНЕ "У-3М"

В.Л. Бережный, В.Л. Очеретенко, О.С. Павличенко, И.Б. Пинос, А.В. Прокопенко, С.А. Цыбенко, А.В. Лозин

Экспериментальными и численными методами проведена идентификация гармоник ВЧ-поля, используемого для создания и нагрева плазмы в торсатроне "У-3М".

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Експериментальними і чисельними методами проведена ідентифікація гармонік ВЧ-поля, яке використовується для створення і нагрівання плазми в торсатроні "У-3М".