ON A POSSIBLE MECHANISM OF RF FIELD HARMONIC GENERATION IN THE NEAR-ANTENNA PLASMA REGION IN THE URAGAN-3M

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A possibility of RF field harmonic generation is shown in the process of plasma formation and heating in the torsatron U-3M when the RF field interacts with a volume spatial charge of positive ions in the near-antenna region.

PACS: 52.55.Hc

In the l=3 torsatron Uragan-3M a plasma is produced and heated by the RF field excited in the ion resonance frequency range $\omega = (0.8\ldots1)\omega_{Bi}$. However, in the spectra of some diagnostics other harmonics are frequently observed, $f_n = n\cdot f_0$ (n=2,3,4…11), with amplitudes of the second harmonic and the third harmonic comparable to the fundamental harmonic amplitude. The excitation of harmonics was related either to nonlinear processes [1] or to the external RF generator itself [2].

In [1] four harmonics were received on the single electric probe; in [2] seven harmonics were found in the frequency spectra of the SHF reflectometer signals and H_α line glow.

In the recent experiments the harmonic reception has been carried out from the plane probes placed nearby the internal helical field windings directly at the harmonic frequency, using a spectrum analyzer [3]. There were not found regularities of the behavior of harmonic amplitudes on the RF voltage applied to a frame type antenna, as well as in the different time intervals of the discharge. As the potentials have been applied to the probe plates, the harmonic amplitudes were almost unchangeable. In the case of disconnecting the entrance cables from the probes, the harmonic amplitudes were decreasing but not vanishing at all. A weak tendency of lower values for the amplitudes of odd harmonics was observed, and sometimes the amplitude of the second harmonic exceeded that of the first one.

The presence of RF field harmonics can cause the power decrease at the fundamental frequency and be the noise disturbance for some diagnostics that complicates the understanding of plasma heating process. Moreover, it is impossible to determine which fraction of the power supplied to the RF antenna is required for plasma formation and heating. At least, the amplitudes and frequencies of the first three harmonics are changing with time equally at the initial stage of plasma formation in the U-3M [4]. This can mean that these harmonics take part in the initial ionization and breakdown of the gas. Thus, shedding light on the mechanism of harmonic generation is of interest in the RF plasma heating experiments.

An important feature of RF discharges is the formation of a space charge (SC) of positive ions near the negative electrode [5]. This SC possesses nonlinear characteristics [6] (i.e., it is a nonlinear element, NLE). At the early beginning of the RF pulse the antenna in the U-3M can be considered as a cold cathode. The result of the interaction between the initial RF wave and the SC is graphically represented in Fig. 1. The RF field can penetrate into the discharge volume only through the SC layer. Taking into account the nonlinear character of the RF field-SC layer interaction, this process can be presented as a sum

$$X_{out}(t) = k[X_{in}(t) + \varepsilon\cdot X^2_{in}(t)]\ . \qquad (1)$$

Then, the pump mode $A_1\cos(\omega t)$ at the SC output will be described by the relation

$$x_{out}(t)=A_1\cos(\omega t)+\varepsilon/2\cdot A_1^2\cos(2\omega t)+\varepsilon/2\cdot A_1^2, \qquad (2)$$

where k=1 is taken for simplification of formulas below.

Thus, at the output of SC not only the main component $\cos(\omega t)$ but also its second harmonic $\cos(2\omega t)$ and the time independent term $\varepsilon/2\times A_1^2$ do appear; the latter indicates the rectification effect takes place.

In some experiments on U-3M two RF generators are used. In such a case the signal at the input on NLE will be: $x_{in}(t) = A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)$, and the signal at the output of NLE will be:

$$\begin{aligned} x_{out}(t) &= \left[A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)\right] + \varepsilon\left[A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)\right]^2 = \left[A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)\right] + \\ &+ \varepsilon\left[A_1^2\cos^2(\omega_1 t) + A_2^2\cos^2(\omega_2 t) + 2A_1A_2\cos(\omega_1 t)\cos(\omega_2 t)\right] = \left[A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)\right] + \\ &+ \left[\frac{\varepsilon A_1^2}{2}\cos(2\omega_1 t) + \frac{\varepsilon A_2^2}{2}\cos(2\omega_2 t) + \frac{\varepsilon(A_1^2 + A_2^2)}{2}\right] + \frac{\varepsilon A_1A_2}{2}\left[\cos(\omega_1 t - \omega_2 t) + \cos(\omega_1 t + \omega_2 t)\right]. \end{aligned} \qquad (3)$$

We see that the SC output signal has not only starting frequencies, ω_1 and ω_2, but the constant term $\Delta = \frac{\varepsilon}{2}(A_1^2 + A_2^2)$ also, what indicates that in this case the process of transformation of rectification of a RF variable component into a constant component takes place also.

However, in addition, two new effects do appear in respect to the case when one wave interacts with SC.

The presence of product of two waves in Equation (3) is the condition of the amplitude modulation of the higher frequency wave amplitude with the wave of the lower frequency, as well as the condition of appearance of the combination frequencies ($\omega_1 \pm \omega_2$). The signals at

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2010. № 6.
Series: Plasma Physics (16), p. 31-33.

a combination frequency of the $(\omega_1 - \omega_2)$ type were observed in experiments on U-3M [7], Fig. 2. In this figure the spectra of SHF reflectometer signals (right) and the Hα line intensity (left) obtained in the same discharge are shown. Arrows indicate the locations of a difference frequency $\Delta\omega = (\omega_1 - \omega_2) = 212\ kHz$.

These data prove the existence of a nonlinear region near RF antenna and the possibility of simultaneous interaction with it of the waves of multiple frequencies, i.e., with harmonics of RF field. If the first and second harmonics are then interacting with the SC, the four RF field harmonics are generated, and so on.

$$x_{out}(t) = A_1(1+\varepsilon A_2)\cos(\omega t) + (\frac{\varepsilon A_1^2}{2} + A_2)\cos(2\omega t) + \varepsilon A_1 A_2 \cos(3\omega t) + \frac{\varepsilon A_2^2}{2}\cos(4\omega t) + \frac{\varepsilon(A_1^2 + A_2^2)}{2}. \qquad (4)$$

At the output of the SC realized are harmonics of three types: initial, and harmonics arising as a result of combination frequencies ($n\omega_1 \pm m\omega_2$). For both types, the number of even and odd harmonics at the output of the SC will be equally probable. The third mechanism of the RF field harmonic generation occurs due to the quadratic nonlinearity of the SC. Therefore, independently on the parity of input harmonics, at the output of the SC only even harmonics are generated. Assuming that the harmonic generation process has an avalanche nature, the interaction of lowest harmonics with the SC leads to the appearance of increasing numbers of higher harmonics. If the first (or the second) harmonic, together with the every next one up to the tenth harmonic, passes simultaneously through the SC, then at its output the realization of up to the twentieth (similar to formula (3)) harmonic occurs including the first eleven ones observed experimentally on U-3M [3]. The results for the case of simultaneous interaction of the first and the next nine harmonics are presented in the Table below. Other, higher harmonics, are not included in the Table.

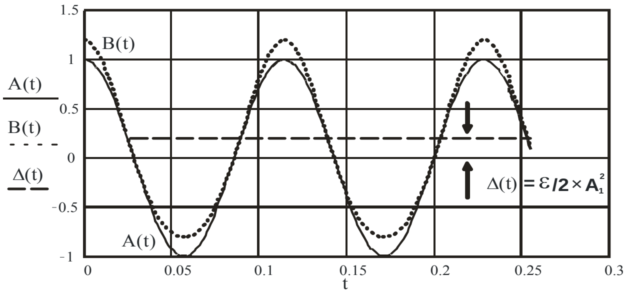

Fig.1. Reactions of linear A(n) (dotted line) and nonlinear B(n) (solid line) elements to the input signal cos(ωt)

The RF field harmonic generation mechanism under consideration confirms a real possibility of exceeding the second harmonic amplitude above the first one ($A_2 > A_1$). An improper reproducibility of amplitudes and the missing regularity of their change in the discharge process can be explained by different variants of every particular harmonic formation. As is known, the overall single-frequency wave amplitude is presented by the process of superposition of all their realization

$$A^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\varphi_1 - \varphi_2), \qquad (5)$$

i.e., it is dependent of both the initial wave amplitudes and their phases. In the limiting case the resulting intensity is changing from $(A_1+A_2)^2$ for $\varphi_1 - \varphi_2 = \pm n2\pi$ ($n = 0, 1, 2, \ldots$) to $(A_1 - A_2)^2$ for $\varphi_1 - \varphi_2 = \pm(2n+1)\pi$ ($n = 0, 1, 2, \ldots$).

Thus, it is shown that when RF field interacts with the NE, the higher harmonics are generated. The second harmonic amplitude can exceed the first harmonic amplitude, as the number of its implementation can be higher. The lack of regularity in the relationship between amplitudes of higher harmonics, observed in experiments, can be connected with the random scatter of the phases of wave that are taking part in generation of every concrete harmonic. According to the Table, the total quantity of the mean value shift:

$$\sum_{n=1}^{10}\Delta_n = \frac{\varepsilon}{2}[A_1^2 + (A_1^2 + A_2^2) + (A_1^2 + A_3^2) + \ldots + (A_1^2 + A_{10}^2). \quad (6)$$

As follows from this example, all generated harmonics are taking part in the process of rectification.

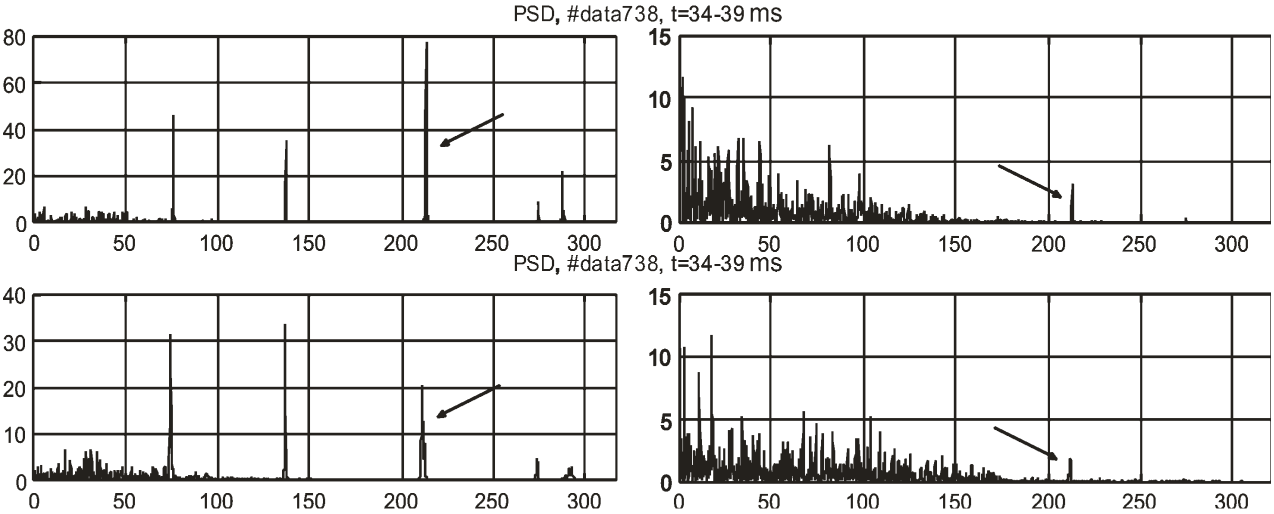

Fig. 2. Combination frequencies $\Delta\omega = \omega_1 - \omega_2 = 212\ kHz$

Amplitudes of the first eleven harmonics at the output of NL

Input waves	Cos2ωt	Cos3ωt	Cos4ωt	Cos5ωt	Cos6ωt	Cos7ωt	Cos8ωt	Cos9ωt	Cos10ωt	Cos11ωt	Δ
A_1Cosωt + + A_2Cos2ωt	$\frac{\varepsilon}{2}A_1^2 + A_2$	$\varepsilon A_1 A_2$	$\frac{\varepsilon}{2}A_2^2$								$\frac{\varepsilon}{2}(A_1^2 + A_2^2)$
A_1Cosωt + + A_3Cos3ωt	$\frac{\varepsilon}{2}A_1^2 + \varepsilon A_1 A_3$	A_3	$\varepsilon A_1 A_3$		$\frac{\varepsilon}{2}A_3^2$						$\frac{\varepsilon}{2}(A_1^2 + A_3^2)$
A_1Cosωt + + A_4Cos4ωt	$\frac{\varepsilon}{2}A_1^2$	$\varepsilon A_1 A_4$	A_4	$\varepsilon A_1 A_4$			$\frac{\varepsilon}{2}A_4^2$				$\frac{\varepsilon}{2}(A_1^2 + A_4^2)$
A_1Cosωt + + A_5Cos5ωt	$\frac{\varepsilon}{2}A_1^2$		$\varepsilon A_1 A_5$	A_5	$\varepsilon A_1 A_5$				$\frac{\varepsilon}{2}A_5^2$		$\frac{\varepsilon}{2}(A_1^2 + A_5^2)$
A_1Cosωt + + A_6Cos6ωt	$\frac{\varepsilon}{2}A_1^2$			$\varepsilon A_1 A_6$	A_6	$\varepsilon A_1 A_6$					$\frac{\varepsilon}{2}(A_1^2 + A_6^2)$
A_1Cosωt + + A_7Cos7ωt	$\frac{\varepsilon}{2}A_1^2$				$\varepsilon A_1 A_7$	A_7	$\varepsilon A_1 A_7$				$\frac{\varepsilon}{2}(A_1^2 + A_7^2)$
A_1Cosωt + + A_8Cos8ωt	$\frac{\varepsilon}{2}A_1^2$					$\varepsilon A_1 A_8$	A_8	$\varepsilon A_1 A8$			$\frac{\varepsilon}{2}(A_1^2 + A_8^2)$
A_1Cosωt + + A_9Cos9ωt	$\frac{\varepsilon}{2}A_1^2$						$\varepsilon A_1 A_9$	A_9	$\varepsilon A_1 A_9$		$\frac{\varepsilon}{2}(A_1^2 + A_9^2)$
A_1Cosωt + + A_{10}Cos10ωt	$\frac{\varepsilon}{2}A_1^2$							$\varepsilon A_1 A_{10}$	A_{10}	$\varepsilon A_1 A_{10}$	$\frac{\varepsilon}{2}(A_1^2 + A_{10}^2)$
Number of realization of every harmonic	12	3	4	3	4	3	4	3	3	1	

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Article received 12.10.10

О ВОЗМОЖНОМ МЕХАНИЗМЕ ГЕНЕРАЦИИ ГАРМОНИК ВЧ-ПОЛЯ В ПРИАНТЕННОЙ ОБЛАСТИ ПЛАЗМЫ ТОРСАТРОНА У-3М

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Показана возможность генерации гармоник ВЧ-поля, используемого для создания и нагрева плазмы в торсатроне У-3М, при его взаимодействии с объемным пространственным зарядом положительных ионов в приантенной области.

ПРО МОЖЛИВІСТЬ МЕХАНІЗМУ ГЕНЕРАЦІЇ ГАРМОНІК ВЧ-ПОЛЯ В ПРИАНТЕННІЙ ОБЛАСТІ ПЛАЗМИ В ТОРСАТРОНІ У-3М

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Показана можливість генерації гармонік ВЧ-поля, що використовується для створення та нагріву плазми в торсатроні У-3М, при його взаємодії з об'ємним просторовим зарядом позитивних іонів у приантенній області.