SPECTRAL ANALYSIS OF ANTENNA RF-CURRENT IN THE TORSATRON U-2M

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The paper deals with the spectral analysis of the antenna RF-current in the torsatron U-2M to elucidate the possibility of improving the efficiency of the RF-technique for plasma formation and heating. The present results show that the improvement in the efficiency of RF power input into the plasma calls for upgrading of both the generator system and the design of the RF antenna and its protection in order to reduce nonlinear interaction of RF waves with the near-antenna plasma.

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INTRODUCTION

The RF range of frequencies is used in magnetic confinement experiments for plasma heating and current excitation. In the U-2M and U-3M torsatrons, the RF technique is also used for plasma formation. In most modes of discharge, two same-type modules of the RF system, hereafter called generator K1 and generator K2, are used. The K1 is used for pre-ionization of hydrogen, while the transition to the quasi-stationary mode of discharge is realized through energizing generator K2. Plasma production and heating by RF techniques involve two major tasks. The first task implies that the RF generator should provide the required power in the necessary frequency range of radiated waves and their optimum transmission to the antenna during the plasma discharge. The second task consists in reducing nonlinear interactions of RF antenna-radiated with the near-antenna plasma, which impair the efficiency of RF power input from the antenna to plasma [1].

1. SPECTRAL FREQUENCY LINES OF ANTENNA RF-CURRENT IN U-2M

The paper presents a certain analysis phase in diagnostic studies of the RF system, performed earlier on the torsatron U-2M. RF antenna was measured using the noiseproof detector. The outline of generator-plasma matching and scheme of measurements are performed in the paper [2]. Frequency-domain analysis of RF current excited on the screenless frame antenna in the U-2M was performed. The part of spectrum (0…10 MHz) from the whole spectrum (0…50 MHz) of the current flowing through the antenna is shown in Fig. 1.

In an early stage of plasma discharge (Δt=3…7 ms), only the first RF generator (K1) was switched on. At this stage, ionization takes place owing to acceleration of background electrons by the RF field of fast magnetosonic waves, and the working gas breakdown occurs. Transient plasma is formed with the electron density $n_e \approx 10^{11}$ cm^{-3}.

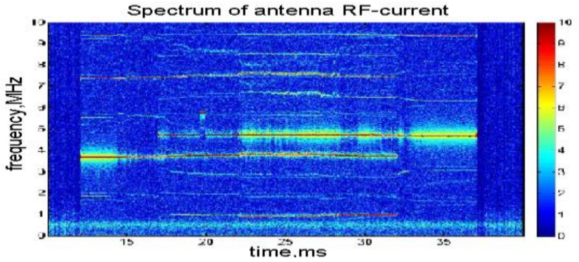

Fig. 1. Spectrum of RF current flowing through the antenna

At this stage of the discharge, harmonics of type $f_n=nf_1$ (where n=1, 2, ... 6; f_1= 3.6875 MHz is the generator K1 frequency) as well as harmonics of type $\Omega= mf_1/2$ (with m= 1, 3, 5, …13) were registered (Fig. 2).

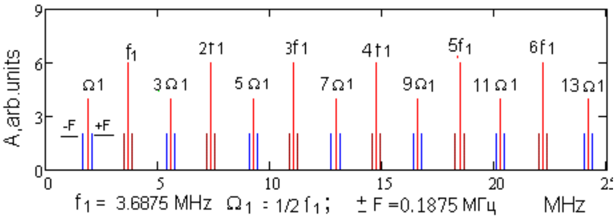

Fig. 2. Harmonics with only K1 operated (Δt=3…7 ms)

The frequencies of all first-type harmonics are integers (multiple of the fundamental frequency). The frequencies of these harmonics are higher them fundamental frequency. These are classical harmonics or harmonic overtones. The second type of harmonics represents a range of half-integral harmonics with the first-harmonic frequency equal to the one-half of the fundamental frequency of the module K1. That is, the harmonics in this case are not the integers and are not multiples of the fundamental frequency. These waves are not the harmonic waves, and that is why these harmonics are called non-harmonic overtones. In spite of the difference between the two types of the harmonics observed, all their frequencies are accompanied on both sides by some unspecified low constant frequency $F \approx \pm$ 0.1875 MHz. The oscillation frequencies of type (f_n-F, f_n, f_n+F), provided that F<<f, are defined as side frequencies.

During the discharge with two generators K1 and K2 (Δt=7…33 ms) switched on, the following harmonics were observed: $f_n=nf_1$ and $f_n=nf_2$, where f_2 = 4.75 MHz is the frequency of the second module K2 of the generator system (Fig. 3).

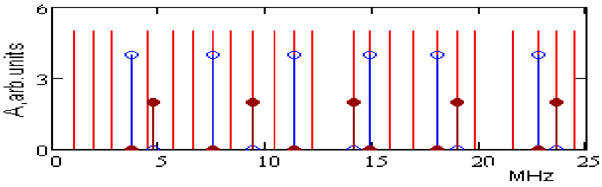

Fig. 3. Combination frequencies (nf_2-nf_1)(straight lines) and harmonics (full and open circles) (Δt=7...21 ms)

The combination frequencies (nf_2-nf_1) were identified in the whole received frequency range up to 25 MHz. This limitation was determined by the Nyquist frequency f_N=50 MHz employed in the detection circuit of RF antenna signals. Therefore, the frequency range is limited by the sixth harmonic ($6f_1$=22.8 MHz) at the fundamental frequency f_1 and by the fifth harmonic ($5f_2$=23.6 MHz) at the fundamental frequency f_2 (see Fig. 3). At the same time, the limiting difference-frequency value was registered between twenty third harmonics ($23f_2$-$23f_1$)=24.48 MHz. The values of identified combination frequencies of the type (nf_2-nf_1) are listed in table.

Combination frequencies of type (nf_2-nf_1), mHz

1	(f2-f1)=1.03125	13	(13f2-13f1)=14.0909
2	(2f2-2f1)=1.9375	14	(14f2-14f1)=14.8701
3	(3f2-3f1)=2.75	15	(15f2-15f1)=15.8442
4	(4f2-4f1)=4.75	16	(16f2-16f1)=16.948
5	(5f2-5f1)=5.625	17	(17f2-17f1)=17.987
6	(6f2-6f1)=6.5625	18	(18f2-18f1)=18.961
7	(7f2-7f1)=7.5	19	(19f2-19f1)=19.8052
8	(8f2-8f1)=8.375	20	(20f2-20f1)=21.5584
9	(9f2-9f1)=9.375	21	(21f2-21f1)=22.7822
10	(10f2-10f1)=10.3896	22	(22f2-22f1)=23.6364
11	(11f2-11f1)=11.2987	23	(23f2-23f1)=24.4805
12	(12f2-12f1)=12.2078		

The participation of large-number harmonics in these process may point to the fact that their amplitudes are not so small. One can also assume the presence of a strong relationship between the antennas of K1 and K2. This is apparent from Fig. 1. At the 22nd ms, there was a small jump in the power pulse supplied to the K2 antenna. At the same time, practically all spectral lines, including the harmonics of the generator K1, showed amplitude-frequency jumps. In other words, a greater number of difference frequency values take place for the harmonics really generated but being beyond the range of harmonic frequency registration. For the same reason, the registration of the combination frequencies of the type nf_2+nf_1 is limited by the second harmonics ($2f_2+2f_1$)=16.875 MHz, and the harmonic ($3f_2+3f_1$)=25.3 MHz goes beyond 25 MHz. All the lines in the interval of discharge from K1 and K2 are presented in see Fig. 3.

It should be noted that some difference frequency lines coincide with certain harmonic frequencies of K1 and K2, and also with the (nf_2+nf_1)- type combination frequencies.

In the final stage of the plasma discharge, (Δt=33…42 ms), with only K2 being on, we identified the harmonics of type ($f_n=nf_2$), and also, the chaotically located indefinite narrow frequency bands in between (Fig. 4).

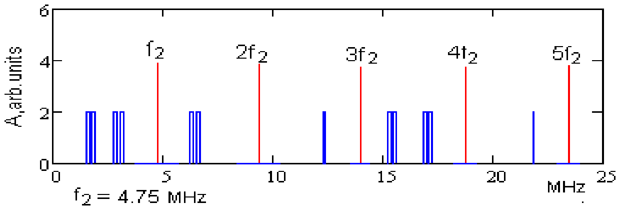

Fig. 4. Harmonics at operation of only K2 (Δt=33…42 ms)

The general spectral recording of the RF antenna current signal during the whole RF discharge is shown in Fig. 5.

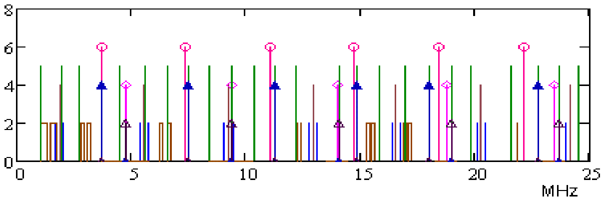

Fig. 5. All spectral frequency lines during the plasma RF discharge (Δt=3…42 ms)

2. DISCUSSION OF RESULTS

In the ideal case, at RF plasma formation and heating, the external generator should provide the necessary frequency spectrum and power. The RF harmonic signal must be delivered to the antenna with minimum distortions and losses. When using two RF generators K1 and K2 in the U-2M torsatron, more than a hundred frequency lines were registered in the course of the plasma discharge (see Fig. 5). In reality, they are much more, considering that the observation was limited to the frequency 25 MHz. The identified lines are the result of three physical effects, viz., generation of higher harmonics at frequencies of K1 (f_1) and K2 (f_2) (see Figs. 2-4, respectively), generation of side frequencies (see Fig. 2), and generation of combination frequencies (see Fig. 3). To one extent or another, these effects can decrease the power level and the quality of RF waves introduced into the plasma. Unfortunately, in the U-2M experiments, the causes of one and the same effect may be different. In the RF system of the U-2M, the generator modules K1 and K2 are made according to identical self-exciting circuits, the disadvantage of which lies in possible generation of higher harmonics [3]. To reduce this generation by the antenna, its relationship with the generator should not be strong. However, the feedback should be sufficient to maintain the necessary ac anode current value of the RF generator. The antenna-plasma coupling efficiency is defined as a fraction of the generator power absorbed by plasma, $\eta=P_{RF\text{-}pl}/P_{RF\text{-}G}$ [4]. Besides, all variations in the electrical parameters of the antenna have an effect not only on the generator frequency, but also on the quality of the radiated waves. On the other hand, with the use of the RF heating technique, the peripheral plasma-antenna system is a strongly coupled nonlinear system [1]. Thus, the RF system of plasma formation and heating in the U-2M torsatron presents the RF generator-antenna-plasma chain with a substantial coupling. As a consequence, the parametric variation in one element of the chain leads to variations in the whole chain loop. With high-amplitude RF voltage applied to the antenna, positive charge layers (PCL) are formed close to the antenna surface [5]. These layers of the uncompensated space charge of positive ions have a pronounced nonlinear current-voltage characteristic (CVC) [6]. In this case, the PCL output can be presented as [7]

$$x_{out}(t)=k[x_{in}(t)+\varepsilon\, x_{in}^2(t)], \qquad (1)$$

where k is the proportionality factor independent of both t and x_{in}, i.e., k=const; $\varepsilon<1$ is the nonlinearity factor. Before entering the plasma confinement volume the RF waves must pass through the PCL. Let two sinusoidal waves enter the PCL

$$x_{in}(t)=A\cos(\omega_1 t)+B\cos(\omega_2 t), \qquad (2)$$

with the close frequencies ω_1 and ω_2 of the both modules of the external RF generator. Then at its output we obtain

$$x_{out}(t)=[A\cos(\omega_1 t)+B\cos(\omega_2 t)]+[\varepsilon/2*A^2\cos(2\omega_1 t)+\varepsilon/2*B^2\cos(2\omega_2 t)+\varepsilon/2(A^2+B^2)]+\varepsilon/2*A*B[\cos((\omega_1-\omega_2)t)+\cos((\omega_1+\omega_2)t)]. \qquad (3)$$

It is evident that the interaction of harmonic oscillations with the PCL results in substantial changes in the incoming waves. Apart from the initial waves, their second harmonics and combination frequencies of type $(\omega_1+\omega_2)$ are formed, and the constant term corresponds to the shift in average between the input sine wave and the output nonsine wave (comprising oscillations of other types). This means that a part of the RF alternating voltage of the initial waves gets rectified giving rise to direct voltage [8]. The nonharmonic overtones (see Fig. 2), which occurred during operation of only one K1, could arise in the external RF generator-antenna circuit, and also, as a result of the occurrence of instabilities at ion cyclotron frequencies during high-power RF heating of plasma. These half-integral harmonics were observed neither at simultaneous operation of K1 and K2 (see Fig. 3), nor at operation of K2 only (see Fig. 4). It should be noted that in spite of the identity of generator modules K1 and K2, there are yet some differences in the generator-antenna matching systems. Besides, the half-integral harmonics were observed only at the initial stage of the discharge, when only K1 was operated. Moreover, in the studies of harmonics in the U-3M torsatron [7] we also registered neither harmonics of type $f_n=n/2*f_1$, nor the side frequencies (f_n-F, f_n, f_n+F), though the same RF generators were used. The side frequencies are the result of amplitude modulation of the RF wave $\cos\omega t$ by the low-frequency wave $\cos\Omega t$ ($\omega>>\Omega$). The amplitude modulation is realized through multiplication (rather than summation) of two oscillations [3, 9]. Such devices belong to the class of nonlinear systems. In the transmitter system the modulation is realized by applying two voltages $U_1=A\cos\omega t$ and $U_2=B\cos\Omega t$ to two pentode grids. The required modulated oscillation can be separated from the anode current by means of a resonant circuit tuned to the frequencies ω. It is difficult to suppose any version of realization of this procedure in the RF generator-antenna system at the U-2M. One can assume the version that the wave-wave interaction followed by the wave multiplication takes place in the PCL, this being quite possible [1]. A high-power wave $\cos\omega t$ enters the nonlinear space-charge layers from the RF-antenna side, and the low-frequency wave $\cos\Omega t$ comes from the plasma side. The frequency Ω = 0.1875 MHz may be quite realistic as a result of occurrence of a certain instability. If the high-power fundamental wave has been amplitude-modulated by the frequency Ω, then the disturbances caused by this frequency in the plasma, and hence, other waves passing through the disturbed region, also appear modulated. This phenomenon is called the intermodulation or cross-modulation [10]. In this way all the harmonics $f_n=n/2*f_1$ (see Fig. 2) can be modulated as they enter the plasma volume through the PCL. Here *n* takes on the values *n*= 1, 2, 3,…. When high-power unmodulated waves propagate, they cause time-constant changes of the plasma parameters, thereby changing propagation conditions of other waves. Besides, there also occur weak varying disturbances with the frequencies being multiples of the disturbing wave frequency [10]. Therefore, the propagation of other waves in the plasma gives rise to the waves with conbination frequencies (see Fig. 3). Analytically, this process has been shown in expression (3). It follows from it that the harmonic generation, combination frequency occurrence and the rectifiability of the RF voltage are peculiar to RF discharges and account for the effect of formation of PCL (also known as rf-sheaths).

CONCLUSIONS

The observed effects may result from nonlinear wave interactions. As regards the generator system, here the non-optimal circuit, mismatch between the circuits and the presence of components with nonlinear characteristics may account for the effects. On the other hand, the edge plasma-antenna system is a strongly nonlinear coupled system [1]. Therefore, even if the pumping waves come to the plasma through the near-antenna layers of the positive space charge having a nonlinear CVC, we observe the formation of harmonics, combination frequencies and the rectification of some part of applied RF voltage. In a constant electric field, the plasma ions get accelerated with the result that the antenna surface degrades and gives rise to a flux of heavy impurities arriving at the plasma, as is the case with U-2M. When using the same generator system, similar nonlinear interactions took place in the torsatron U-3M [7, 11]. The present results show that the improvement in the efficiency of RF power input into the plasma calls for upgrading of both the generator system and the design of the RF antenna and its protection in order to reduce nonlinear interaction of RF waves with the near-antenna plasma.

The arrival of heavy impurities at the plasma from the RF antenna surfaces takes place during their bombardment by ions accelerated in the constant electric field [1,11]. This process can be essentially reduced by means of boronizing of all the surfaces facing the plasma inside the vacuum chamber [12]. The antenna surface coating with a thin film from low-z material can substantially improve the efficiency of plasma RF heating in the U-2M torsatron.

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REFERENCES

1. I.R. Myra, D.A. Ippolito, D.A. Russel, et al. Nonlinear ICRF plasma interactions // *Nuclear Fusion*. 2006, v. 46, № 7, p. 455-468.
2. V.V. Filippov, V.B. Korovin, D.L. Grekov, E.D. Kramskoj, and Uragan-2M team. Update of Radiometry of RF Complex Kaskad-1 and Measurements of RF Parameters // *International Conference-School on Plasma Physics and Controlled Fusion and The Adjoint Workshop "Nano- and micro-sized structures in plasmas*", Kharkov, Ukraine, September 15-18, 2014 /Book of Abstracts, 2014, p. 43.
3. I.P. Zherebtsov. *Radiotekhnika*. Moscow: "Svyaz", "Sovetskoye radio", 1965 (in Russian).
4. A. Lissoivan, R. Koch, D. Van Eester, et al. ICRF plasmas for fusion reactor applications // *Problems of Atomic Science and Technology. Series "Plasma Physics"(13)*. 2007, № 1, p. 30-34.
5. V.A. Godyak. A stationary low-pressure RF discharge // *Fizika Plazmy*. 1976, v. 2, № 1, p. 141 (in Russian).
6. V.A. Godyak, A.A. Kuzovnikov. On electrical valve-like action of RF discharges // *Fizika Plazmy*. 1975, v.1, №3, p. 496 (in Russian).
7. V.L. Berezhnyj, I.V. Berezhnaya, V.S. Voitsenya, et al. On a possible mechanism of RF field harmonic generation in the near-antenna plasma region in the Uragan-3M // *Problems of Atomic Science and Technology. Series "Plasma Physics" (16).* 2010, № 6, p. 31-33.
8. S.M. Levitsky. The space potential and electrode sputtering in the RF discharge // *ZhTF*. 1957, v. XXVII, iss. 5, p. 1001-1009 (in Russian).
9. G.S. Gorelik. *Oscillations and waves*. Moscow: "State publishing house for phys. math. Literature", 1959, p. 133 (in Russian).
10. V.L. Ginzburg. *Propagation of electromagnetic waves in plasma* / Ed. by Moscow: "Nauka", 1967.
11. V.L. Berezhnyj, I.V. Berezhnaya, V.S. Voitsenya, et al. Effects of RF field rectification and accelerated electron beam generation in the torsatron U-3M during plasma production // *Problems of Atomic Science and Technology. Series "Plasma Physics"(17).* 2011, №1, p. 26-28.
12. S.J. Wukitch, B. LaBombard, J. Lin, et al. ICRF specific impurity sources and plasma sheaths in Alcator C-Mod // *Journal of Nuclear Materials*. 2009, v. 390-391, p. 951-954.

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СПЕКТРАЛЬНЫЙ АНАЛИЗ ВЧ-ТОКА АНТЕННЫ В ТОРСАТРОНЕ У-2М

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Проведен спектральный анализ ВЧ-тока антенны в торсатроне У-2М с целью поиска возможности увеличения эффективности RF-метода создания и нагрева плазмы. Представленные в работе результаты показывают, что для увеличения эффективности ввода ВЧ-мощности в плазму необходимо усовершенствовать как генераторную систему, так и конструкцию ВЧ-антенны и ее защиту с целью ослабления нелинейного взаимодействия ВЧ-волн с приантенной плазмой.

СПЕКТРАЛЬНИЙ АНАЛІЗ ВЧ-СТРУМУ АНТЕНИ В ТОРСАТРОНІ У-2М

В.Л. Бережний, В.В. Філіппов, В.Б. Коровін, І.В. Бережна

Проведено спектральний аналіз ВЧ-струму антени в торсатроні У-2М з метою пошуку можливості збільшення ефективності RF-методу створення та нагріву плазми. Представлені в роботі результати показують, що для збільшення ефективності введення ВЧ-потужності в плазму необхідно удосконалювати як генераторну систему, так і конструкцію ВЧ-антени та її захист з метою ослаблення нелінійної взаємодії ВЧ-хвиль з приантенною плазмою.