# ELECTROMAGNETIC OSCILLATIONS AT THE EDGE OF THE URAGAN-3M PLASMA

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In the Uragan-3M torsatron the plasma is ICRF heated with the use of antennas of different types. The objective of this work is to study the electromagnetic wave propagation outside the plasma confinement volume and the effect of these waves on confined plasma behavior during RF-heating.

PACS: 52.55.Dy, 52.55.Hc

## INTRODUCTION

In our experiments we used the so-called "frame" and "three-half-turn" unshielded antennas [1]. With this heating technique, it was believed for a long time that almost all the power irradiated by antenna was absorbed by the plasma in the confinement volume and there are no electromagnetic waves between the helical coils and the plasma. Also, it was believed that non-propagating electromagnetic oscillations are generated within the antenna area. Later on, it was shown [2, 3] that the RF power absorbed in the confined plasma is only a small part of that irradiated by the antenna. The problem is where the rest of the power is absorbed and what its effect is on plasma behavior in the confinement volume. Basing on the experimental data obtained here, it is suggested that electromagnetic waves propagate outside the confinement volume too. These waves ionize and heat the plasma with the density of $n_e \approx 10^9 \ldots 10^{11}$ cm$^{-3}$, which screens the fuelling gas entering the confinement volume. The term "RF plasma screening" was also proposed [3].

## EXPERIMENTAL CONDITIONS AND RESULTS

To study electromagnetic waves that propagate away from the antennae outside the region of plasma confinement away during the RF heating (Fig. 1), two magnetic probe arrays are used located in the spacing between the helical winding and the confinement region. Probes close to the confinement volume are located 2 cm distant from it, the distance between the arrays being $l = 3$ cm. Each array consists of 3 coils oriented on 3 orthogonal components of the magnetic field. Since the radiation pattern of probes is not acute, there is an evident coupling between the probes of one array. The A1 antenna current is recorded using a special loop. The bandwidth of the magnetic probes with the recording section attains 80 MHz, and that of the loops measuring the antenna current exceed 140 MHz. The fundamental frequency where the plasma heating is observed is near 9 MHz and differs for various antennas. The analysis of the signals picked up by the probes is carried out using the correlation analysis.

The effect of RF waves propagating outside the confinement volume on plasma behavior in the confinement volume is studied using a 2 mm interferometer to determine the average density, a sensor of soft X-Ray radiation and optical systems recording radiation from the plasma in the visible range.

In this operational mode of RF generator plasma does not have an effect on current in the antenna and the oscillation spectrum shown in Fig. 2 corresponds to the fundamental frequency of the RF generator. The spectrum of the antenna current is rather wide (about 6 MHz half-width). There are also higher frequencies, up to 80 MHz. The phase shift $\varphi$ between the antenna current and probe is 0 or $\pi$ over the whole frequency range studied.

As is shown in Figs. 3 and 4 where the plasma is RF heated at the average density $n_e \leq 2x10^{12}$ cm$^{-3}$ in the confinement volume, using the frame antenna, the frequency spectrum of the antenna current changes significantly.

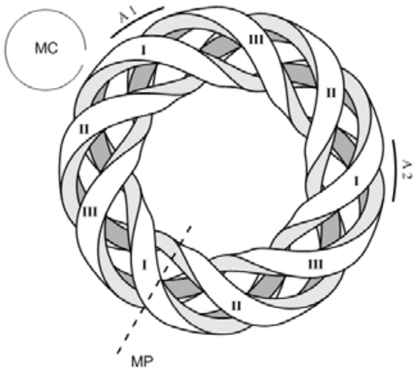

*Fig. 1. Helical windings of the Uragan-3M torsatron. The poloidal cross-section where the magnetic probes (MP) are placed is indicated by the dashed line. The sectors where the frame and three-half-turn antennae are installed are labeled as A1 and A2, respectively. MC - loop recording current in the antenna A1*

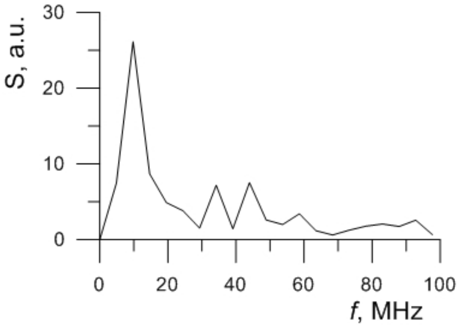

*Fig. 2. Oscillation spectrum of the frame antenna current without plasma*

Time behavior of the current in the antenna and signals from two probes similarly oriented in the radial direction 3 cm separated from each other is presented in Fig. 3. The results of processing of these signals are shown in Fig. 4.

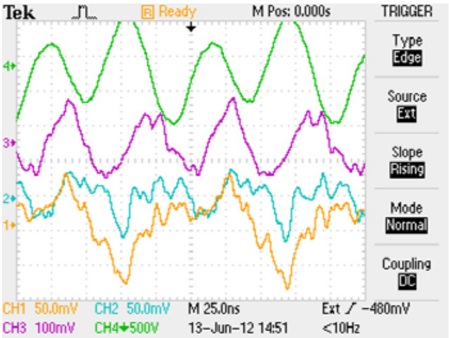

*Fig. 3. Signals from the radially oriented magnetic probes 1 and 2 and antenna current 4 with plasma heating using the frame antenna*

Fig. 3 shows time behavior of signals from different groups of probes (traces 1 and 2) and current in antenna (trace 4). It is clear that the probe signals are of one order by amplitude. Their spectra of oscillations are given in the Fig. 4 where frequencies up to $f \approx 100$ MHz are observed. However, oscillations in the $f \leq 25$ MHz region dominate in their amplitude. The low-frequency parts of the spectra taken from the probes ($f \leq 20$ MHz) differ significantly. In one of the probe harmonics with $f \approx 10$ MHz dominate, while the frequencies $f = 10$ and 20 MHz dominate in another probe. This spectrum is similar to that of the antenna current. The phase shift between the oscillations from different probes indicates the presence of the radial phase velocity for waves propagating in the space between the confinement volume and helical winding.

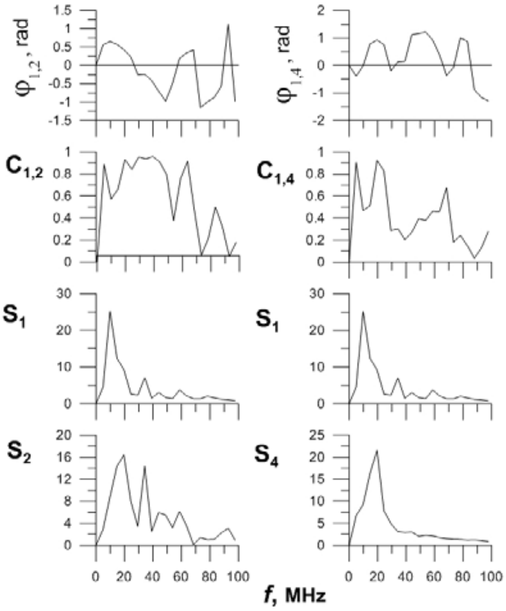

*Fig. 4. Results of processing of signals shown in $\varphi_{1,2}$ and $\varphi_{1,4}$, phase shifts at different frequencies for probes 1…2 and 1…4; $C_{1,2}$ and $C_{1,4}$, coherence spectra; $S_1$, $S_2$, $S_4$, auto-spectra of signals from probes 1, 2 and 4, respectively*

The phase velocities of these waves $V_{ph} = fl\varphi/2\pi$ have different direction for different frequencies of the spectrum, their values increase with frequency and lie in the range of $V_{ph}=2 \cdot 10^6 \ldots 4 \cdot 10^7$ cm/s. A typical feature of this heating regime is an increase of oscillations with frequencies $f = 15$ and 20 MHz, so that the amplitude of these oscillations is comparable to the amplitude on the main frequency $f \approx 9$ MHz. So, there are conditions for oscillations at $f \approx 20$ MHz with $\omega/\omega_{ci} \approx 1.6$, to propagate in the plasma. The role of these oscillations on plasma heating has not been cleared yet.

In the plasma heating regimes where the frame and tree-half turn antennae heat the plasma simultaneously, the amplitudes of the high frequency oscillations (up to 80 MHz) undergo a significant increase (Figs. 5, 6) and become comparable to those at the fundamental frequency $f \approx 10$ MHz. A typical feature of this heating regime is the absence of correlation between the groups of probes on the frequency of $f \approx 20$ MHz. The phase velocities of wave propagation in this regime are similar to those in the previous case.

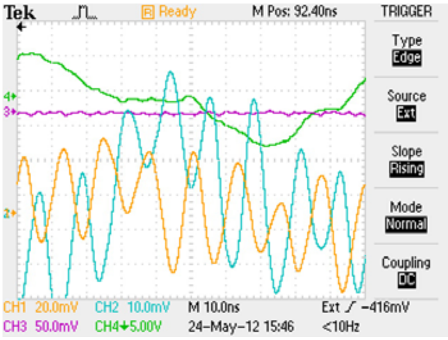

*Fig. 5. Signals from poloidally oriented magnetic probes 1 and 2 placed in different probe arrays and frame antenna current 4 with plasma heating using frame and three-half-turn antennae simultaneously. $S_1$, $S_2$, $S_4$, auto-spectra of signals from probes 1, 2 and 4, respectively*

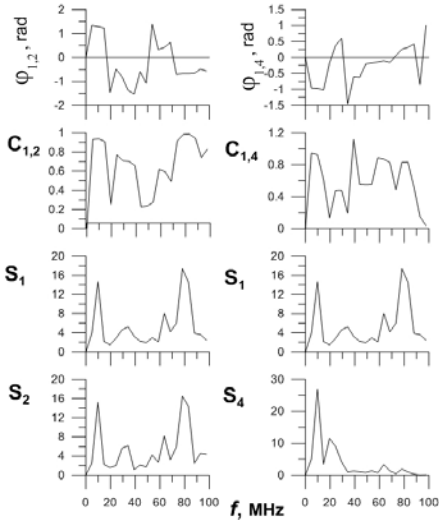

*Fig. 6. Results of processing of signals shown in $\varphi_{1,2}$ and $\varphi_{1,4}$, phase shifts at different frequencies for probes 1…2 and 1…4; $C_{1,2}$ and $C_{1,4}$, coherence spectra; $S_1$, $S_2$, $S_4$, auto-spectra of signals from probes 1, 2 and 4, respectively*

Absorption of powerful electromagnetic oscillations in a thin plasma layer outside the confinement volume should result in heating of this plasma despite a small time of particle confinement here. However, it is the low confinement time that causes a significant increase of plasma bombarding the metal environment and increase of impurity release. Besides, the plasma outside the confinement volume could ionize the neutral gas, thereby limiting its influx into this volume.

In order to verify these assumptions, a special experiment was carried out. At a certain moment of discharge the RF power irradiated by the antenna was suddenly raised, and corresponding changes in plasma parameters in the confinement volume were recorded (Fig. 7).

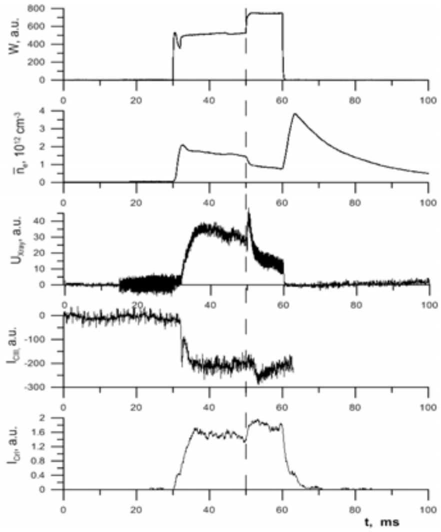

*Fig. 7. Effects of RF heating power W increase on plasma density $n_e$ in the confinement volume, the intensity of soft X ray $U_{XRay}$, carbon $I_{CIII}$ and chromium $I_{CrIII}$ lines*

## CONCLUSIONS

Using magnetic probes located outside the confinement volume, it is shown that electromagnetic waves relating to the RF plasma heating propagate in this space. The frequency spectrum of these waves depends on heating features and its high frequency part could be related to the development of plasma instabilities. Estimations show that the RF power spent for generation of these waves could exceed 100 kW.

The interaction of RF waves outside the confinement volume with the low-density plasma strongly affects plasma behavior in the confinement volume. The following effects were observed:

- screening of the hydrogen influx to the confinement volume (RF screening);
- impurity influx rise from metallic components facing the plasma, and from the antennas, first of all.

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*Article received 01.11.12*

## ЭЛЕКТРОМАГНИТНЫЕ КОЛЕБАНИЯ В ПЕРИФЕРИЙНОЙ ПЛАЗМЕ УРАГАН-3М

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В торсатроне Ураган-3М плазма нагревается ВЧ-волнами вблизи ионно-циклотронного резонанса антеннами различных типов. Целью настоящей работы является изучение распространения электромагнитных волн вне объема удержания и влияния этих волн на параметры плазмы в течение разряда.

## ЕЛЕКТРОМАГНІТНІ КОЛИВАННЯ В ПЕРИФЕРІЙНІЙ ПЛАЗМІ УРАГАН-3М

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У торсатроні Ураган-3М плазма нагрівається ВЧ-хвилями поблизу іонного-циклотронного резонансу антенами різних типів. Метою цієї роботи є вивчення поширення електромагнітних хвиль поза обсягу утримання і впливу цих хвиль на параметри плазми протягом розряду.