DEVELOPMENT OF THE SYSTEM FOR MULTICHANNEL MICROWAVE PLASMA PROBING IN THE TORSATRON U-2M

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To study successfully the conditions for production and heating of the plasma, its dynamics in the process of an RF discharge in the torsatron U-2M, a multichannel system for microwave diagnostics is suggested. To obtain the electron density profiles with an asymmetric plasma cross-section in the *l*=2 torsatron, 5 fan channels and 3 longitudinal channels will be used. For these measurements a quadrature interferometer at a frequency of 140 GHz is under development.

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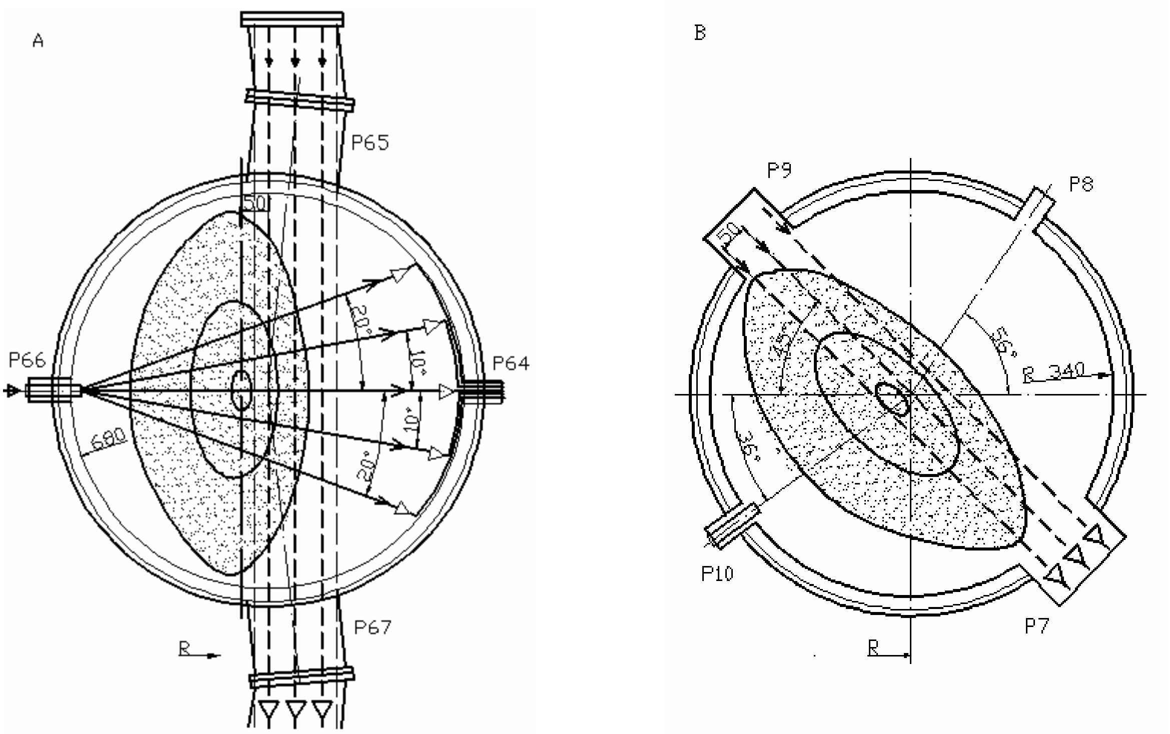
To study the conditions for production and heating of the plasma, and its dynamics in the process of an RF discharge in the torsatron U-2M, a multichannel system for microwave diagnostics will be used. The main destination of this system is to determine the electron density spatial distribution n_e and its fluctuations $\delta n_e/n_e$. Taking into account the installation design and plasma column cross-section [1], the most optimum variant is the use of five fan channels for electron density measuring along the major plasma oval axis and three channels along the minor plasma oval axis [2], Fig.1. For these purposes two independent microwave interferometers with heterodyne detection of phase (φ) are intended to be designed.

In this device, operating under optimum conditions ($K_\varphi = B_{th}/B_0 = 0.32$, B_{th} is the toroidal magnetic field produced by the helical winding, B_0 is the total toroidal magnetic strength) the plasma density can reach the value above $1\cdot10^{19}$ m^{-3}. With such an electron density value the refraction at peripheral probing channels can lead to the distortion of information obtained. For the plasma column with a cylindrical symmetry and parabolic distribution of the electron density $n_e(r) = n_0[1-(r/r_0)^2]$ by probing with a paraxial microwave beam the refraction angle will be

$$\theta = \frac{2n_0}{n_{cr}\cdot\varepsilon_0}\cdot\frac{x_0}{r_0}\sqrt{1-\left(\frac{x_0}{r_0}\right)^2}\,, \qquad (1)$$

where n_0 is the density on the axis, n_{cr} is the critical density for the given probing frequency, ε_0 is the dielectric permittivity of the plasma on the axis, x_0 is the impact parameter, r_0 is the plasma radius. This formula cannot be applied to conditions of the torsatron U-2M. In the mode $K_\varphi = 0.32$ the magnetic axis is shifted inwards from the geometrical axis by ~ 5 cm. The plasma cross-section has a form of an oval with a major axis of ~ 60 cm and a minor axis of ~ 30 cm. Nevertheless, the analysis of equation (1) can give general fruitful results – the less is the n_0/n_{cr} for any given probing wavelength, the less is the refraction angle, and θ possesses the maximum value at $x_0/r_0 = 0.7$. Because of the beam bending, the physical path length increases what leads to the change in the amplitude of a signal detected S = A·cosφ. On the other side, the beam gets into the different-value density $n_e = f(a)$ along the probing beam path (a) than it might be in the case if the beam passes without refraction directly. The errors due to the refraction of probing beams are of the same order of magnitude. Displacement of probing beam center $\Delta x = l\cdot\mathrm{tg}\theta$ relatively to the receiving horn center was calculated for the equal distance l = 60 cm from the transmitting antenna to all the receiving antennas. From this it follows that the receiving antenna should be installed as close to the plasma as possible. The limits for electron density measurement by means of microwave interferometers in the U-2M for three lengths of probing waves with taking into account other possible regimes of operation are given in the Table below. Here the lower density limit is determined by the unique determination of the phase φ = 2π. This limit can be significantly decreased to sevearal degrees depending on the type of interferometer in use. The upper limit of plasma density is restricted by the value of critical electron density for the given length of the probing wave. Substantially, the upper limit of the electron density being measured in the periphery region of the plasma is decreased by the refraction effects. To minimize the refraction effects, one should: optimize the construction and arrangement of microwave elements inside the discharge chamber [3], use the quadrature interferometers with heterodyne phase indication, select a rather high probing frequency with taking into account the maximal value of n_e. The quadrature interferometer has two separate output sygnals S_1 = A·cosφ and S_2 = A·sinφ with a phase shifted by π/2. Interpretation of quadrature interferometer data is unambiguous even if the phase is changing by many π/2 values. The quadrature interferometer has not ambiguity in the determination of the differential response dφ/dt. As one signal approaches an extremum, the other channel is in the middle of its range, so that the sign of dφ/dt is never uncertain. Therefore, the data interpretation is unambiguous even when the phase is changing by many orders of magnitude. For the quadrature interferometer it is characteristic that the constant A has one and the same time variation of every signal, when the amplitude of the phase envelope amplitude is changing as a result of diagnostic beam bending because of the refraction. Thus, the algorithm of the analysis of quadrature interferometer data $\varphi = \mathrm{arctg}(S_2/S_1)+n\cdot\pi/2$ is correct even in the presence of refraction effects [4].

Five fan probing channels are realized within the limits of the transmitting antenna directivity diagram (~ 40°) therefore, the input power should be sufficient to provide measurements along the lateral probing channels. The ratio of a power in the outer channel to that in the central one, with taking into account the real geometry of the torsatron U-2M, is ~ 0.5 when the open waveguide of 1.8×3.6 mm cross-section is used as a radiator (see Fig. 1, a). The measured values of the average electron density by five chords allow to determine its distribution along the central part (~20 cm) of the major axis of the plasma oval. Because of the absence of plasma column cylindrical symmetry it is intended to carry out the probing for the three channels along the major size of the oval, spaced at a distance of 43 mm, in the same plasma column section (Fig. 1a), using the diagnostic ports P65 – P67. However, because of the inclination of these flanges by 6° outwards the vertical axis of the plasma chamber and the shift of the geometrical axis of the plasma oval inwards by 5 cm in the operating mode of the installation ($K_\varphi = 0.32$) the external channel passes beside the plasma column. It can be used as a control one, in the case of variations $B_\perp/B_0$, for comparison between the data and the probing measurements of the SOL plasma. As an alternative, these three probing channels are recommended to be doubled in the other plasma column section, using the diagnostic ports P9 – P7 (Fig. 1b).



a *b*

Fig.1. Geometrical position of probing beams of the microwave interferometers at the torsatron U-2M between the diagnostic ports: a) P66 – P64 and P65 – P67; b) P9 – P7

Refraction influence on the interferometric measurements of the electron density in the plasma of the torsatron U-2M

N_0, 10^{17} m^{-3}	8	10	20	40	60	80	100	150	200	400	600	700	1000	2000	3000
$\lambda_{probe} = 8$ mm θ_{max}, ° ΔX, mm	- -	0.116 1.13	0.24 2.3	0.51 5.0	0.82 8.0	1.17 11.4	1.58 15.4	3.03 29.6	----- -----	----- -----	----- -----	----- -----	------ ------	------ ------	------ ------
$\lambda_{probe} = 4$ mm θ_{max}, ° ΔX, mm	- -	------ ------	0.057 0.55	0.12 1.12	0.17 1.71	0.24 2.37	0.31 3.0	0.47 4.58	0.67 6.51	1.56 15.3	2.99 29.3	----- -----	------ ------	------ ------	------ ------
$\lambda_{зонд} = 2$ mm θ_{max}, ° ΔX, mm	- -	------ ------	------ ------	0.03 0.27	0.04 0.41	0.06 0.55	0.07 0.69	0.11 1.05	0.14 1.41	0.3 2.94	0.47 4.58	0.65 6.33	0.85 8.3	2.17 21.2	------ ------

In this section all the three channels traverse the plasma column (Fig. 1b) due to displacement relatively to the equatorial torus plane of the spatial magnetic axis of the magnetic surfaces' configuration. However, the distance between the channels in this section is slightly less (~30 mm). Measurements in the both these sections can provide five values of the average density along the major size of the plasma oval. Using these data, it is possible to calculate the electron density distribution along the minor axis of the plasma oval.

Realization of the microwave heterodyne interferometer is based on the synchronization of the transmitting and heterodyne oscillators by means of a common quartz source. Moreover, for both, the microwave oscillators [5], as well as, the corresponding harmonics of RF oscillators can be directly used.

Simultaneously the algorithm design is under development for automation of plasma electron density profile construction by the results of interferometric measurements. Some of probing channels will be used also for measuring the electron density $n_e(a)$ and its fluctuation ($\delta n_e / \overline{n}_e$) in the measurements on the reflectometry and scattering of microwaves.

The above-mentioned methods of electron plasma density diagnostics make it possible to represent the density spatial distribution that will promote the solving of other problems on investigations of the plasma in the torsatron U-2M.

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РАЗРАБОТКА СИСТЕМЫ МНОГОКАНАЛЬНОГО МИКРОВОЛНОВОГО ЗОНДИРОВАНИЯ ПЛАЗМЫ В ТОРСАТРОНЕ У-2М

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Для успешного изучения условий создания и нагрева плазмы, ее динамики в процессе ВЧ-разряда в торсатроне У-2М создается многоканальная система микроволновой диагностики. Для получения профилей плотности электронов с неосесимметричным сечением плазмы в двухзаходном торсатроне будет использовано пять веерных и три продольных канала. Для этих измерений разрабатывается квадратурный интерферометр на частоте 140 ГГц с гетеродинной индикацией фазы.

РОЗРОБКА СИСТЕМИ БАГАТОКАНАЛЬНОГО МІКРОХВИЛЬОВОГО ЗОНДУВАННЯ ПЛАЗМИ В ТОРСАТРОНІ У-2М

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Для успішного вивчення умов створення і нагріву плазми, її динаміки в процесі ВЧ-розряду в торсатроні У-2М створюється багатоканальна система мікрохвильової діагностики. Для одержання профілів густини електронів з невісесиметричним перерізом плазми в двозаходному торсатроні буде використано п'ять віяльних і три подовжні канали. Для цих вимірювань розробляється квадратурний інтерферометр на частоті 140 ГГц з гетеродинною індикацією фази.