Using refraction during interferometry of plasma

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Abstract. The calculation of ray tracing for microwaves at 36 GHz frequency depending on the different maximum values of density was made. The calculation showed when rays hit or do not hit into the horn antenna shifted at angle 60º degrees with respect to the axis of the radiating horn antenna. In addition, the calculated and experimental measurements of the phase shift dependence in time for the through and inclined probing were performed. The use of refraction during interferometry can give additional information about plasma when the through probing interferometry is impossible.

1. Introduction
The development and the progress of researches in plasma physics are determined by the development of methods for measuring plasma parameters. Among methods of plasma diagnostics, microwave methods occupy an important place. They are divided into active and passive ones. In passive methods, microwave radiation emitted by plasma is measured. The active wave diagnostic systems [1] probe the plasma dielectric properties by measuring the wave phase (interferometry [2]) and polarization changes (polarimetry [3]) when passing the plasma and probe the localization of cut-off layers (reflectometry [4]).

The microwave methods by using refraction of microwaves in inhomogeneous plasma can be used in plasma diagnostics. These methods are feasible only with an inclined microwave probing. To have a full set of data, the angle of the transmitting horn antenna should be varied with respect to the plasma (see Figure 1a), what in practice is not always technically possible. In the case when there is no possibility to vary this angle, it was proposed [5, 6] to use the rays diverging from the transmitting horn antenna directed at an oblique angle to the plasma (see Figure 1b). In this case, the method can be suitable. The experimental results in the mentioned papers demonstrate that by use of the interferometry methods based on refraction, the evaluation of an average plasma density in the peripheral layers of plasma volume is principally possible. The purpose of this work is to show the possibilities of using refraction during interferometry of plasma by the inclined probing.

2. Description of the experiment
2.1. Experimental installation
Experiments on the microwave interferometry by using the inclined and through probing of plasma were carried out on the experimental installation ‘MAKET’. A high-power impulse reflex discharge in crossed $E\times B$ fields was realized. A schematic drawing of the experimental installation ‘MAKET’ is shown in Figure 2. There are main parameters of the experimental installation in table 1. More information about this installation is in the paper [7].
Figure 1. Refraction of microwave ray in a plasma cylinder. Transmitting (1) and receiving (2) horn antennas, (3) plasma. $\Psi$ - the angle between the line of propagation and the cylinder radius at the point of ray incidence on the plasma cylinder. $\Theta$ - the deflection angle of the ray radius-vector from its position on entering the plasma.

Table 1. The main parameters of the installation

| Parameters          | Values      | Parameters          | Values      |
|---------------------|-------------|---------------------|-------------|
| **Discharging system:** |             | **Magnetic system:** |             |
| Discharge voltage   | $\leq 5$ kV | Magnetic induction  | $\leq 0.9$ T |
| Pulse time          | $\sim 4$ ms| Pulse time          | 18 ms       |
| Discharging current | $< 2$ kA   | Mirror ratio        | 1.25 R      |
| Battery capacity    | 560 $\mu$F | Battery capacity    | 12 mF       |
| Stored energy       | $\leq 7$ kJ| Stored energy       | 54 kJ       |
| **Other valuable values of the installation and tip** | | **Other valuable values of the installation and tip** | |
| Volume of vacuum chamber | ~ $7 \cdot 10^4$ cm$^3$ | Plasma volume | ~ $10^4$ cm$^3$ |
| Operating pressure  | 0.133-4.7 Pa| Ignition gas       | Argon       |
| Cathode diameter    | 10 cm      | Cathode material   | Zirconium   |

By convention, the time behavior of the mean gas-metal plasma density can be divided into three stages [7]. The first stage consists in the plasma creation and its density increase up to $N_e = 1.7 \cdot 10^{13}$ cm$^{-3}$ (duration is tens-hundreds $\mu$s). In this stage, the gas gap break-down takes place, and the self-sustaining discharge with the cold cathodes gets ignited. The formation of weakly ionized plasma $N_e < 1 \cdot 10^{11}$ cm$^{-3}$ occurs due to ionization of neutral molecules (atoms) by primary electrons emitted from the cathode surfaces. Note that the plasma electrons can also contribute to the gas ionization. In this case, the cathode sputtering takes place and the sputtered atoms come to the plasma. The second stage presents the existence of the dense ($N_e \geq 1.7 \cdot 10^{13}$ cm$^{-3}$) highly ionized plasma (duration of several milliseconds). In this stage, a further increase in the plasma density takes place up to the
maximum value, which is determined by the balance between the processes of plasma particle production and losses. In this case, the plasma density can attain \( N_e \approx 10^{14} \text{ cm}^{-3} \). At a later time, the processes leading to plasma particle losses become predominant, and the plasma density decreases. Here we note that out of the processes leading to plasma losses, the processes of plasma recombination, particles diffusion across the magnetic field and particles leaving to the magnetic mirror are dominant. The third stage presents the plasma density decrease and decay (duration up to 12 milliseconds).

![Figure 2](image)

**Figure 2.** A schematic image of the experimental installation ‘MAKET’. 1 - cathodes; 2 – a vacuum chamber (anode); 3 - the magnetic system; 4 - horn antennas; 5, 7 - insulators; 6 - the vacuum-pumping system; A-A, B-B - sections of diagnostic ports (all dimensions are in centimeters).

### 2.2. Diagnostic technique

The amplitude-phase measurements of the probing signal are performed by two pairs of interferometers. Interferometers are shown in Figure 3 and installed in section A-A with this sequence: at the beginning – the 1st pair, then – the second pair. The radiated power of the generator 1 is divided by waveguide multi-hole couplers. For each branch of waveguides, the amplitude of microwave signal is regulated by attenuators 2, 3 and 7. Phase adjustments for maximum phase sensitivity are made in the reference path with the help of phase shifters 4 and 8. Figure 3a shows the measuring scheme for the first pair of interferometers: for the through and inclined probing. For the interferometer by using the through probing, the receiver horn antenna 11 registers the transmitted signal. For the interferometry by using the inclined probing, the horn antenna 13, shifted at the angle 60° degrees with respect to the radiating antenna axis 12, registers the transmitted signal. Figure 3b shows the second pair of interferometers: for the through and inclined probing. In the case of inclined probing, the axis of the receiving horn antenna 13 is shifted at the angle 120° with respect to the radiating antenna 11. The reference signal and signal passing through the plasma are combined at diodes 6 and 10 for the inclined and through probing, respectively. It is important to say that the inclined probing is realized due to microwaves rays, which fall to the plasma at an oblique angle relative to the plasma column. The plasma cylinder is probed using an ordinary wave (O-wave) at the frequency \( f = 36 \text{ GHz} \). Considering the horn antenna aperture, the angle of microwave radiation registration amounts to \( \phi_1 \approx 60° \pm 9°, \phi_2 \approx 120° \pm 9° \). The resulting signals from the detectors 7 and 6 were amplified 10 times by a broadband amplifier and recorded with a digital oscilloscope. The digital oscilloscope has 25 MHz bandwidth and 100 MS/s sample rate. Signal-to-noise ratio (SNR) is 20 dB.
Figure 3. Schematic representation of the measuring system with using two pairs of interferometers: a – first pair, for the through and inclined probing (receiving antennas shifted at the angle 60°), b – second pair, for the through and inclined probing (receiving antennas shifted at the angle 120°). 1 – generator; 2, 3, 7 – attenuators; 4, 8 – phase shifters; 5, 9 – the matched loads; 6, 10 – phase detectors; 11, 12, 13 – horn antennas.

3. Features of microwave interferometry by using the inclined probing

3.1. Microwave trajectories in the plasma cylinder

The calculation of microwave trajectories at frequency 36 GHz are shown in Figure 4. The equations of geometrical optics approximation were used for the calculations. The axis of the radiating horn antenna was situated at an angle of φ = 0° (the angle of flare is 9°), the axis of the receiving antenna was situated at an angle of φ = 300° (the angle of flare is 9°). The microwave ray trajectory was calculated considering the aperture of the horn antennas and taking the density distribution of plasma in the form of

\[ N_p(r) = N_{p0}(1-(r/R)^2) \]

into account.

In the geometrical optics approximation, the differential equation for the trajectory of a microwave ray in a plasma cylinder looks like [8]:

\[ \frac{d\phi}{dr} = \frac{R \sin \Psi}{r^2 \sqrt{n_0^2(r) - R^2/r^2 \sin^2 \Psi}}, \]  

where \( \Psi \) is the angle between the line of propagation and the cylinder radius at the point of ray incidence on the plasma cylinder; \( \phi \) is the deviation angle of the radius-vector from its initial position; \( R \) is the cylinder radius; \( r \) is the current coordinate; \( n_0 \) is the refraction index for the O-wave.

Figure 4 shows 3 cases when rays hit or do not hit to the shifted horn antenna with taking into account different maximum plasma density in the center of the cylindrical cross-section. In the first case, when the maximum plasma density is less than the critical \( (N_p < N_{cr}) \), microwave rays, due to refraction deviate from the rectilinear propagation, pass through the plasma and do not hit the receiving horn antennas. In the second case, the maximum plasma density is greater than the critical density \( (N_p > N_{cr}) \) wherein the microwave rays reflect from the plasma layer with a critical density and can fall into the receiving antenna shifted at angle of 60° with respect to radiating antenna. In the third case, the maximum plasma density is greater than the critical \( (N_p > N_{cr}) \) too. Calculation shows that when the radius of the plasma layer with \( N_{cr} \) is greater than 6.3 cm, microwave rays do not enter the horn antenna.
3.2. Experimental and calculated results of phase shifts

In the case of cylindrical symmetry, when the additional phase due to reflection is taken into account, the phase of the electromagnetic wave transmitted through the plasma is defined as [9]:

\[
\Phi_{\psi}(t) = \frac{2\phi}{c} \int \frac{n^2(r)dr}{\sqrt{n^2(r)r^2 - R^2 \sin^2 \Psi}} - \frac{\pi}{2}
\]

(2)

where refraction index \( n(r) = \sqrt{1 - \frac{N_{\text{max}} F(r)}{N_{\text{cr}}}} \), \( F(r) \) – plasma profile (see fig. 5a). \( F(r) = (1 - (r/R)^2) \).

\( N_{\text{max}} \) – the maximum concentration of electrons at the axis of the plasma cylinder.

From the equation 2, we may conclude that the phase shift depends on the size of the region occupied by the plasma, the plasma density and its profile, the angle of incidence of microwave into the plasma cylinder. We made calculations for phase shift at angles \( \Psi = 0 \) and when \( \Psi \neq 0 \). The case \( \Psi = 0 \) corresponds to the interferometry by using the through probing and the case \( \Psi \neq 0 \) corresponds to the interferometry by using the inclined probing. Calculations were made for the probing microwave length 0.8 cm what corresponds to the critical concentration of plasma electrons \( 1.7 \cdot 10^{13} \text{ cm}^{-3} \). For the calculation in the case of the inclined probing the average value of the maximum and minimum phase of the rays were taken into account only for those rays which hit into receiver horn antenna shifted at 60° with respect to radiating antenna axis. As follows from calculations, at \( N_{\text{max}} < N_{\text{cr}} \) the ray propagates through the plasma without hitting this receiver horn antenna. Therefore, it was assumed in the calculations that the microwave rays reflect from the opposite surface of the chamber and fall into the antenna. In other words, microwave beams passed through the plasma twice. Hence, our calculations performed with rather simplified assumptions demonstrated some features and the difference between the phase shifts measured at plasma interferometry with oblique microwave beams and interferometry through the center of a plasma formation. Under real experimental conditions, the phase shift evolution in time can be more complicated. For both pairs of interferometers from Figure 5 and 7, it is seen that with decreasing density the phase shift also decreases. It is known that when the plasma density exceeds the critical one, the application of the interferometry method for the through probing is impossible. At the same time, an electromagnetic wave at the inclined probing after the reflection from the plasma layer with a critical density can hit into a receiving antenna shifted at some angle with respect to the axis of the radiating antenna. Therefore, in the case when a probing signal is received at 60° the phase shifts can be registered (see Figure 6a) even if the plasma density is above the critical value. So in our case, by using interferometry at 60° it is possible to determine a time dependence of the product plasma density \( N_p L \) (\( L \) the optical path length of the microwave rays in a vacuum) in the interval from 2 to 4 ms (Figure 6b). However, an electromagnetic wave can enter the receiving antenna only up to a certain value \( N_{\text{max}} \), when the radius of plasma with the critical layer is
less than 6.3 cm for the receiving at 60°. If the value of $N_{\text{max}}$ is exceeded, therefore, the radius of the critical layer is exceeded too, so the measurement of phase shifts is impossible for the through and inclined (60°) probing.

Figure 5. The time dependence of $N_{\text{max}}$ (a) and the phase shift (b). The interferometry by using: 1 – the through probing, 2 – the inclined probing (60°).

Figure 6. Experimentally measured time dependence of phase shift (a) and of the product $N_p L$ (b). The curve 1 – represent interferometry by using the through probing, curve 2 – represent interferometry by using the inclined probing (60°).

Figure 7. The time dependence of $N_{\text{max}}$ (a) and the phase shift (b). Interferometry by using: 1 – the through probing, 2 – the inclined probing (120°).
From the Figure 8a, it can be emphasized, that the time dependence of the phase shifts for the wave received by the antenna 13 (see Figure 3b) is close to the time dependence of the phase shifts for wave transmitted through the plasma center. Like in the previous case described above, the measurement of the phase shift for the inclined probing $120^\circ$ can be made even if through probing is impossible. This makes it possible to determine the product of $N_pL$ at a density slightly higher than the critical density $N_{cr}$ (see Figure 8b). As can be seen from Figure 8b, starting from the 2.5 milliseconds the value of $N_pL$, measured by both interferometers, began to be slightly different. This is due to the fact that the length of the optical path for the microwave rays at the oblique and through probing is different. Since $L$ depends not only on the density but also on the plasma profile, so it can be assumed that the plasma density profile also changes with time. As was shown earlier in [7], in the initial period of plasma decay, the main mechanism of particle loss is recombination, and at a later stage - diffusion of particles across the magnetic field. Accordingly, this may lead to a change in the plasma density profile.

**Figure 8.** Experimentally measured time dependence of phase shift (a) and time dependence of product $N_pL$ (b). 1 – interferometry by using the through probing, 2 – interferometry by using the inclined probing $(120^\circ)$.

### 4. Conclusion

The calculations of microwave trajectories for rays at 36 GHz frequency for different maximum values of plasma density, were carried out. It was determined the cases when the microwave rays hit or do not hit into receiving horn antenna shifted at the angle of 60° with respect to the axis of the radiating antenna. In addition, it was experimentally measured and calculated the phase shift of the transmitted wave received by the antennas shifted at the angles $120^\circ$ and $60^\circ$ with respect to the axis of the radiating antenna. The time dependence of the phase shifts registered by the antenna shifted at the angle of $120^\circ$ with respect to the axis of the radiating antenna is close to the time dependence of the phase shifts for the wave transmitted through the center of the plasma column. It is shown that interferometry with using the inclined probing can provide information about the time dependence of the product $N_pL$ on the periphery of plasma, during the time when by interferometry through the plasma axis, the cutoff of the signal is observed.

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