Method for determining plasma density in a magnetic field

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Abstract. A new method is proposed for measuring plasma density based on the direct determination of the phase shift of an electromagnetic wave during the passage of probe radiation through plasma using a broadband oscilloscope. The paper describes a scheme for measuring plasma density up to $4 \times 10^{13}$ cm$^{-3}$. Examples of using this method to determine the parameters of the inductively coupled plasma and plasma flows in a magnetic field are given.

1. Introduction
Modern methods of microwave plasma interferometry allow measuring plasma density in a wide range from $10^8$ cm$^{-3}$ up to $10^{14}$ cm$^{-3}$ [1,2]. A classical scheme of the interferometer is following: a probing wave passes through the plasma, is received by the antenna, and then compared with the reference wave; amplitude equalization is achieved in the absence of plasma using variable attenuators and a phase shifter in both channels; the determination of the phase difference between the reference and plasma-transmitted signals is carried out by adding the signals and measuring the amplitudes in each of the channels, and extracting a signal proportional to the phase difference. Currently, phase detection systems can measure the minimum phase shift of $0.01$ – $0.003^\circ$ [3].

We propose a new method for measuring plasma density based on the direct determination of the phase shift of an electromagnetic wave passing through plasma using a broadband oscilloscope. In our case, both signals (probe and reference) are recorded on the oscilloscope, and then the phase difference between them is determined. Oscilloscopes with a bandwidth of up to 110 GHz and a sampling rate of up to 200 GS/s have now appeared on the market. The phase shift between the reference and the signal passed through the plasma is reconstructed by numerical methods using the recorded waveforms. Plasma density measurements by recording real-time oscillograms of the probing wave field have an advantage over traditionally used detectors for recording the envelope of microwave radiation. Firstly, this approach can significantly increase the accuracy of determining the phase shift in the unstable plasmas. Secondly, it allows taking into account the phase instability of the reference signal. Thirdly, it enables work in conditions of significant radiation absorption by the plasma.

1 www.keysight.com/en/pdx-2935714-pn-UXR1102A/110-ghz-2-channel-uxr-series-real-time-infiniium-oscilloscope
2. Measurement circuit
The measurement scheme used is shown in Figure 1. A generator based on a Gunn diode with a waveguide output WR15 was used as a source of probe radiation. It generates continuous electromagnetic radiation with frequencies 57-59 GHz, with a power of 20-30 mW. The microwave radiation was recorded by a receiving waveguide path connected to a Keysight DSOZ594A oscilloscope (59 GHz bandwidth, 160 GS/s sampling frequency, minimum temporal resolution of 6.25 ps).

![Diagram of plasma density measurement.](image)

The scheme uses a directional coupler, which directs about 1% of the incident power as a reference signal, which is fed to the oscilloscope through a coaxial-waveguide junction. The main power reaches the object under the study (plasma) through the open end of the waveguide, passes through it and enters through the waveguide and the coaxial-waveguide transition to the second input of the oscilloscope. Oscillograms of the reference wave signal and the signal transmitted through the plasma object are recorded in real time on an oscilloscope. During the measurement, the phase difference between these signals is recorded with and without a plasma object. These values determine the phase shift associated with the object under the study. The phase shift determines the refractive index and, consequently, the plasma density averaged over the probing wave path. The plasma density distribution over the radius is assumed to be uniform further.

The recorded waveforms with the duration of at least 1 us were numerically processed to receive the phase shift between signals. The Discrete Fourier Transform (DFT) is done for both reference signal and the signal passed through a plasma volume. The reference frequency is determined as a peak frequency in the Fourier spectrum of the reference signal. Then its phase is calculated as an angle of a complex Fourier harmonic [4]. The same algorithm is implemented for the second waveform. The phase shift is determined as a difference between two calculated phases. We assume that the phase shift change for two consecutive measurements with different experimental conditions is less than \(\pi\) and is changing monotonically. This allows us to align phase shift measurements into the same \(2\pi\)-domain.

3. Experiments
3.1. Inductively coupled plasma
The technique was tested on an inductively coupled discharge. Figure 2 shows a photograph of the general view of the setup. The discharge chamber is a quartz tube with a diameter of 5 cm, placed in the winding of the inductor. A Cesar generator operating at a frequency of 13.56 MHz with power up to 600 W was used as a source of external high-frequency electromagnetic field. The waveguides were
located 1 cm below the inductor, the probing wave propagates in a horizontal plane, and the polarization of radiation is vertical.

![General view of the installation of inductively coupled plasma.](image)

Figure 2. General view of the installation of inductively coupled plasma.

![Dependence of the density of inductive coupled plasma on heating power.](image)

Figure 3. Dependence of the density of inductive coupled plasma on heating power. Circles represent the classical interferometer scheme, squares represents the direct measurement of the phase shift.

Figure 3 shows the dependence of the measured electron density of the nitrogen plasma on the heating power. The measurements were carried out at a pressure of 0.02 Torr. To verify the method under the same conditions, the electron density was measured using a microwave interferometer, made in the classical scheme. Unlike the method described above for measuring the phase shift through a plasma, in the classical scheme of an interferometer it occurs by adding the probe and reference signals by a quadratic microwave detector. Using a phase shifter in the waveguide line, it is possible to adjust the phase difference between these signals. By measuring the phase difference with the medium
and without medium, it is possible to calculate the phase shift due to the object under study. The detailed interferometer circuit is described in the [5]. Gunn diode with a frequency of 33 GHz was used as a source of microwave radiation in that case. The output power was 110 mW, the phase noise level of the source was not more than $\pi/30$. This made it possible to measure the electron density in the range from $1.19 \times 10^{11}$ cm$^{-3}$ to $3.4 \times 10^{12}$ cm$^{-3}$. The results of measuring the plasma density by the classical scheme are also shown in Figure 3. You can see that the results obtained by different methods are the same, which confirms the reliability of the proposed method. Also, probe measurements of electron density in nitrogen plasma were carried out on this setup. Langmuir double probe was located on the axis of the gas discharge chamber. The obtained local values of the electron density in the center of the plasma column are 2 times higher the average value of the electron density obtained by interferometers along the course of the probe beam.

### 3.2 ECR discharge

The most interesting application of the proposed method is the density measurement of plasma confined in the magnetic field. The use of contact measurement methods in magnetoactive plasma is usually impossible. We performed our studies using a gas discharge sustained by the electromagnetic radiation of a gyrotron in the magnetic field under electron cyclotron resonance (ECR) conditions.

Sketch of the experimental facility is shown in Figure 4. Continuous-wave radiation (TE11 mode) of gyrotron with a frequency of 24 GHz, propagates through the plasma coupling device into the center of discharge chamber. The construction of plasma-coupling device provides the transmission of more than 90% of gyrotron power, also protecting the gyrotron from reflected radiation from plasma and plasma fluxes. The power level of the microwaves can be varied from 0.1 to 5 kW.

![Figure 4. Sketch of the experimental setup.](image)

The discharge chamber is realized as a cylindrical stainless tube (32 mm in diameter) with a length of 60 cm. A copper grid with holes of 3 mm in diameter is installed at the end of the discharge chamber opposite the microwave inlet, forming a microwave cavity. The gas supply (argon, nitrogen, air) to the discharge chamber is controlled by a precision leak valve installed next to the microwave inlet. The chamber is evacuated by oil-free forevacuum, providing the limiting residual pressure in the diagnostic chamber of $(1-2) \times 10^{-3}$ Torr. The experiments described in this paper were made in the air at operating pressure range of $(1-5) \times 10^{-2}$ Torr. To create ECR conditions, the discharge chamber is partly
placed in the magnetic field which is formed by water-cooled Bitter-type magnetic coil. The experimentally measured dependence of the magnetic field value on the axis of the chamber on the longitudinal coordinate is shown in Figure 5. The maximum magnetic field in the coil is about 1 T with a current of 750 A. The gas breakdown and plasma heating are performed under electron cyclotron resonance conditions at the fundamental harmonic of the gyrofrequency. The ECR absorption region occupies the position near the center of the magnetic coil and corresponds to the magnetic field strength of 0.86 T for 24 GHz. Two 10 mm in diameter stainless tubes with CF40 flanges in the center of the discharge chamber were used to facilitate microwave diagnostics of plasma parameters. The plasma density was measured at the distance of 6 cm from the maximum of the magnetic field.

![Magnetic field distribution along axial direction.](image)

Figure 5. Magnetic field distribution along axial direction.

Figure 6 shows the dependence of the plasma density, reconstructed from the phase shift of the probe radiation as a function of the heating power at a gas pressure of 26 mTorr. The phase incursion in the path corresponding to the plasma diameter (3 cm) did not exceed π/4 in these measurements. As can be seen from Figure 6, starting with a power of heating radiation of 100 W, there is a sharp increase in plasma density, after which, at power above 250 W, the density practically does not change. The
average plasma density in this case reaches 1.1*10^{12} \text{ cm}^{-3}. If we assume a decrease in density along magnetic field lines, then at the maximum of the magnetic field the plasma density reached values close to the cut-off value for a heating wave (7.1*10^{12} \text{ cm}^{-3} for 24 \text{ GHz}), which is typical of ECR discharges [6,7]. When plasma reaches a cut-off density, the heating efficiency drops significantly due to the reflection of heating radiation.

4. Conclusion
The method of measuring plasma density by the direct determining of phase shift of the probing signal has been experimentally demonstrated in the inductively coupled plasma and in the magnetoactive plasma of electron cyclotron resonance discharge. In the plasma of ICP discharge in nitrogen the averaged plasma density attained the value of 6*10^{11} \text{ cm}^{-3} at the pressure of 20 mTorr. In the ECR discharge plasma density at the maximum magnetic field reached the value of (5-9)*10^{12} \text{ cm}^{-3} which corresponds to the cut-off density. The proposed method can be applied up to cut-off plasma density for the probing radiation frequency (4*10^{13} \text{ cm}^{-3} for 59 \text{ GHz}) and also under conditions of significant absorption of the probing wave.

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