MICROWAVE RESONATOR PROBE DIAGNOSTICS OF PLASMA DENSITY FLUCTUATIONS

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The unique diagnostics of the low frequency waves excited in magnetoplasma was tested on large “Krot” device. Method is based on measuring the resonance curve frequency and amplitude modulation of a tiny double-wire probe caused by plasma density variations. Depending on the operating point position at the probe resonance characteristic we can measure density fluctuations down to $\delta n/n \le 10^{-5}$. The possibility of harmonic and non-periodic density perturbation measurements is shown in experiments. We also demonstrate the possibility of using the resonator probe as a noninvasive medical tool to diagnose the pathologies and diseases accompanied by changes in tissue complex dielectric coefficient.
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1. INTRODUCTION

The resonant devices with distributed electrodynamics parameters are widely used in microwave probing of materials. [1]. The insertion of the tested material into the electromagnetic field of device (or probe) leads to probe resonance curve modification (central frequency shifting and Q-factor changing). The dielectric and magnetic properties of the medium under study can be analyzed using the parameters of such modifications. The simplest microwave resonator represents a double-wire section. Various probes designed using this basic element are often utilized for artificial and natural materials diagnostics

The microwave resonator probe of the double-wire section is successfully used for localized plasma density measurements and its variations detection [2]. In contrary to the conventional Langmuir electrostatic probes, the results of microwave resonator probe measurements in a linear mode are determined only by plasma density, and not affected by electron temperature value. In [3] the nonlinear effects are studied, which are caused by ponderomotive action of the electric fields on the plasma particles surrounding the probe tips. In particular, it was shown that the probe operated in a non-linear mode could be used for electron temperature measurements.

In present paper the microwave resonator probe properties are studied in the context of diagnosing the non-stationary processes in a magnetoplasma, which are accompanied by weak plasma density perturbations caused by electrostatic fields excitation. We have studied the spatial distribution of non-stationary electron density variations, caused by loop antenna action in the low-hybrid frequency range; experimental data were compared with the numerical results. Also the plasma density oscillations in an area of intense low-hybrid wave interaction with plasma were observed.

2. EXPERIMENTAL ARRANGEMENT AND MEASUREMENT TECHNIQUE

The experiments, in which the microwave resonator probe was used for quasiperiodic plasma density perturbations measurements, were performed on “Krot” plasma facility [4]. Device represents a vacuum vessel 3 m in diameter and 10 m in length (Fig.1). Plasma column is created using radio-frequency inductive discharge (f=5MHz, τ_p=1ms, B_0=80G) in argon under pressure $5{\cdot}10^{-4}$ Torr. The experiments were performed in afterglow plasma, after the plasma source switching off. The characteristic time of plasma decay is of order of 10 ms.

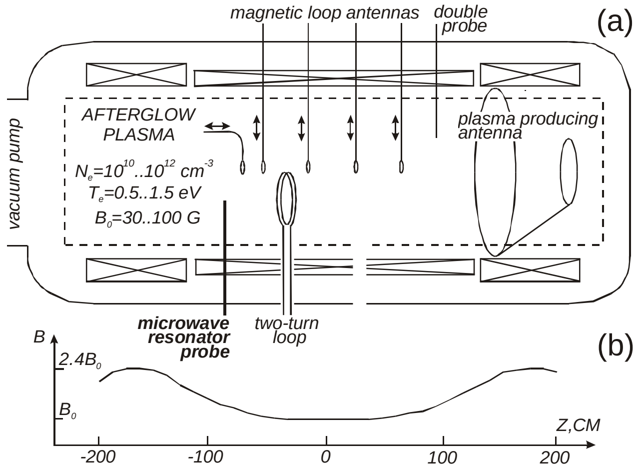

Fig.1. Schematic view of the “Krot” facility (a); ambient magnetic field distribution (b)

During experiments two shielded loop antennas were used: (i) single-turn, radius 1 cm, wire section 3 mm, and (ii) double-turn, radius 10 cm, wire cross-section 2.5 см. The loop plane normal was oriented along the lines of the ambient magnetic field. The radio-frequency pulses with the length τ_p=1ms were applied to the loops. Electron density fluctuations were measured using microwave resonator probe installed on a shaft movable in the radial direction.

The microwave resonator probe used for low-temperature plasma diagnostics is shown schematically on Fig.2.

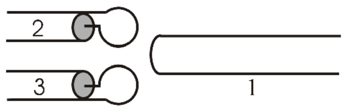

Fig.2. Schematic view of microwave resonator probe: 1 – microwave resonator, 2, 3 – excitation and reception lines

The probe represents a quarter-wavelength section of the double line, which is shortened at the one end, and is opened at the opposite end. It was constructed from the copper wire; probe tips length was 8 mm, wire cross-section – 0.2 mm, the space between the tips – 2 mm. Microwave resonator excitation and its response were performed at the shortened end, by two loops with the diameter 2 mm. The resonator frequency was F ~ 8 GHz, its Q-factor was Q ≈ 100. As it was shown in [2], the resonance frequency ω_{res} of the probe immersed into plasma is determined by density N of the plasma surrounding the resonator: $\omega_{res}^2 = \omega_0^2 + \omega_{pe}^2$, where ω_{pe}- electron plasma frequency. Small plasma density perturbation in the form $\delta n \cos(\omega_m t)$ leads to periodic variations of the probe resonance frequency. For the fixed frequency, taken at the slope of the probe resonance curve, the periodic variations of ω_{res} value can transform into the amplitude modulation of the signal at a perturbation frequency; so, modulation index is proportional to the slope gradient $dU_{res}/d\omega$.

If we take the operating point at the maximum gradient of the resonance slope for the analysis of non-stationary density variations, then signal modulation index δU_{res} is connected with a plasma density perturbation δn by the following relation

$$\frac{\delta U_{res}}{\max(U_{res})} \approx \frac{Q_0}{2\left(1+\omega_0^2/\omega_{pe}^2\right)} \frac{\delta n}{N}. \qquad (1)$$

The limitations of density perturbation δn diagnostic technique proposed are stipulated by perturbation frequency value ω_m : inverse value of the latter could be higher than characteristic resonant system response time in respect of medium parameters variations: $T^* = Q/\omega_{res}, \omega_m^{-1} > T^* \sim 2 \cdot 10^{-9}$ s. Schematic diagram of the measuring system is presented at Fig. 3. Microwave oscillator is connected to the excitation line of the probe. The signal after receiver loop is fed to waveguide-to-coaxial adapter, with subsequent detection, and pass to the narrow-band receiver input ($\Delta f = 100$ kHz), which is used for modulation of the resonance curve analysis. The output of the receiver is connected with a digital oscilloscope and PC.

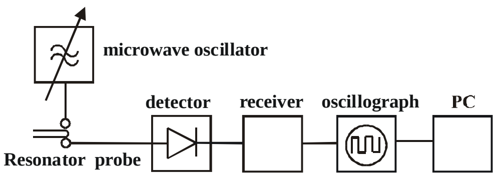

Fig.3. Schematic diagram of the measurement system for periodic plasma density perturbation study using microwave resonator probe

3. EXPERIMENTAL RESULTS

In experiments the spatial structure of the plasma density perturbation at the distance 1 cm from the loop antenna plane with a radius R=1 cm was studied. The measurements were performed in plasma of density $N=3 \cdot 10^{11} cm^{-3}$ and electron temperature T_e=1.5 eV with ambient magnetic field strength B_0=80 G. The frequency of the signal fed to antenna was 80 MHz, its power was 60 W.

The typical resonance curve trace and the trace of the amplitude modulation envelope obtained during studies of the periodic electron density fluctuations in afterglow decaying plasma are shown at Fig.4. The amplitude modulation δU_{res}, and hence the amplitude of density fluctuations, were proportional to the strength of the current in the loop antenna.

The Fig. 5 shows the radial distribution of density oscillations amplitude δn at a distance 1 cm from the of a loop antenna with radius R=1 cm. It can be seen the minimum of δn at r=0, at the interval between 0 and R the density perturbation monotonically increases, with the subsequent decrease with a scale length ~ R.

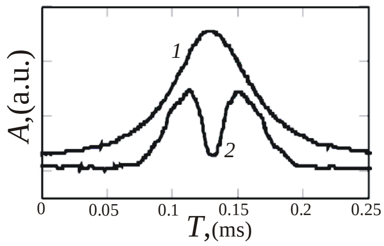

Fig.4. The typical oscilloscope traces of the resonance curve (1) and the amplitude modulation envelop (2)

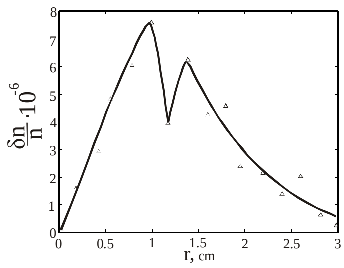

Fig. 5. Radial distribution of the δn at a distance 1 cm from the plane of the loop antenna with radius 1 cm

4. NEAR-FIELD NON-DESTRUCTIVE DIAGNOSTICS FOR THE INHOMOGENEOUS MEDIA

The near-field measuring system utilized for low-conductance objects probing is shown schematically at Fig.6a. The probe represents a microwave resonator described above. This probe interacted with the material under study by measuring part 4 of the resonator 1, representing a section of the double line shortened at the one end, and opened at the other. The resonator free frequency was 860 MHz; Q-factor of the resonant system was 150. For the probing of the high-conductance objects the resonator from half-wavelength section shortened at the both ends was used, see Fig.6b.

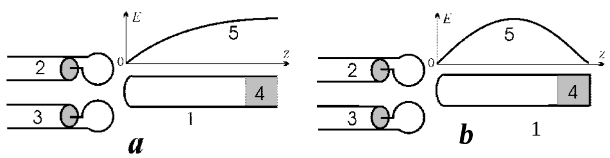

Fig.6. The measuring systems used: a – probe with a quarter-wavelength resonator, b – probe with a half-wavelength resonator: 1 – microwave resonator, 2 and 3 – excitation and reception lines, 4 – the measuring part of the resonator. 5 – electric field distribution along the resonator

This scheme provides the minimization of the insertion loss. The measuring part of the resonator corresponds to the electric field minimum in this case. The resonator free frequency was 860 MHz, its Q-factor was 200. The interaction of quasi-electrostatic field of the probe with the inhomogeneous object causes the resonator frequency shifting, and changing of resonator Q-factor. The theory of microwave resonator probe operation in respect of magnetized plasma density and temperature diagnostics was developed in [3]. For this theory it is essential that the probe operating frequency is higher than a plasma frequency. Dielectric constant of plasma in this case is very close to unity, so the iteration procedure can be used for calculations of capacitance per unit length. In our case (Fig.6) microwave resonator interacts with the object under study only by small part of itself, as a result a small parameter can be extracted, thus the technique developed in [3] can be utilized.

The probe sensitivity was studied in the model experiments described below. The sample of homogeneous medium with the linear dimensions much higher than measuring resonator part length *d* was chosen. We studied the resonance curve of the probe behavior versus distance *h* between the flat sample surface and the measuring part of the resonator. Fig.7 shows the shift of the resonance frequency versus distance *h* for two materials – teflon and glass. The trace shows that frequency shift is greatest in case of direct contact with the sample, and is diminishing with the increase of the distance *h*. The maximum probing depth h_{cr} matches with the gap between the tips of the probe *d=6 mm* with high accuracy.

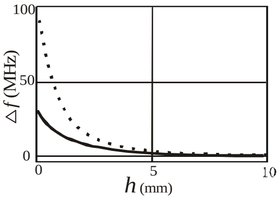

Fig.7. Resonance frequency shift Δf versus distance h to the sample surface with ε = 6.75 (solid line) and ε=2 (dashed line)

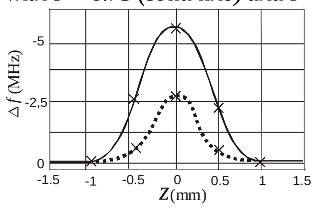

Fig.8. Resonance frequency shift Δf of the probe versus its lateral position during studies of psoriatic papule with a diameter 1 cm. Solid line – before the beginning of the therapy, dashed line – after the therapy course beginning

Relating to the biological tissue pathologies diagnostics, the near-field technique under development was approved in Research Institute of Dermatology and Venereology (Nizhniy Novgorod, Russia) in studies of the human skin affected by psoriasis. It was discovered that dielectric constant and conductivity of the affected tissue are smaller than in case of healthy skin. During the recovery period the electrodynamics parameters of the skin affected became closer to healthy skin parameters. Fig.8 shows the resonance frequency shift Δ*f* versus position of the resonator measuring part center during studies of the psoriatic papule of diameter 1 cm – before the beginning of the therapy course, and during recovery period. The patients' examination during the course of treatment let us reveal the dynamics of their recovery at the stages, which are not characterized by visible changes of the skin affected by psoriasis. Thus the near-field technique of the psoriatic papules.

CONCLUSIONS

The experiments performed have shown that the microwave resonator probe constructed from the double-wire section can be successfully applied as a diagnostic tool for the measurements of non-stationary processes in magnetized plasma, accompanied by plasma density perturbations $\delta n / n$ of order $10^{-5} – 10^{-6}$.

The possibility is shown of using the proposed resonant system as a non-destructive diagnostics of the arbitrary dielectric media. Using the skin disease example, we show the possibilities of measuring system with resonator of double-wire section as a tool for near-field diagnostics for pathologies of a biological tissue.

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ИЗМЕРЕНИЕ НИЗКОЧАСТОТНЫХ ФЛУКТУАЦИЙ ПЛОТНОСТИ ПЛАЗМЫ ЗОНДОМ С СВЧ-РЕЗОНАТОРОМ

А.В. Костров, А.И. Смирнов, А.В. Стриковский, Д.В. Янин

На экспериментальном стенде «Крот» реализована оригинальная диагностика амплитуды низкочастотных волн, возбуждаемых в замагниченной плазме. Метод основан на измерении частоты и амплитуды модуляции резонансной частоты миниатюрного проволочного резонатора, вызываемых флуктуацией плотности плазмы. Измеряются флуктуации плотности порядка $\delta n/n \leq 10^{-5}$. В качестве приложения, продемонстрирована возможность применения резонансной системы для диагностики не только плазмы, но и произвольных диэлектрических сред без нарушения их целостности. Анализируются такие вопросы, как глубина зондирования, возможность определения пространственных и электродинамических характеристик неоднородностей. Демонстрируется возможность применения методики в медицине.

ВИМІР НИЗЬКОЧАСТОТНИХ ФЛУКТУАЦІЙ ГУСТИНИ ПЛАЗМИ ЗОНДОМ З СВЧ-РЕЗОНАТОРОМ

О.В. Костров, А.І. Смирнов, А.В. Стріковський, Д.В. Янін

На експериментальному стенді «Крот» реалізована оригінальна діагностика амплітуди низькочастотних хвиль, порушуваних у замагніченій плазмі. Метод заснований на вимірі частоти й амплітуди модуляції резонансної частоти мініатюрного дротового резонатора, що викликаються флуктуацією густини плазми. Виміряються флуктуації густини порядку $\delta n/n \leq 10^{-5}$. Продемонстровано можливість застосування резонансної системи для діагностики не тільки плазми, але і довільних діелектричних середовищ без порушення їхньої цілісності. Аналізуються такі питання, як глибина зондування, можливість визначення просторових і електродинамічних характеристик неоднорідностей. Демонструється можливість застосування методики в медицині.