29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-1.130 (2002)*

A Resonance Microwave Probe Based on a Two-Wire Line Section

I.G. Kondrat`ev, A. V. Kostrov, A. I. Smirnov, A. V. Strikovsky,
Institute of Applied Physics RAS, GSP-120 ,
Nizhny Novgorod - 603950, Russia

Resonance sensors (probes) often used for plasma diagnostics are very sensitive even to minor changes in parameters of the media, which they are placed in. Main sources of information in such sensors are shifting and expanding of the resonance curve. As a rule, researchers aim at the probe's introducing minimal perturbations into the surrounding plasma, though these perturbations can be also used for diagnostics.

The report proposed describes a plasma resonance microwave probe based on a section of the two-wire line . An important feature of this probe is that even in the case of a comparatively weak exciting signal, nonlinear effects start to appear in such a probe, which are associated with the striction action of microwave fields on the plasma. The authors of the report develop the nonlinear theory of the resonance microwave probe based on a two-wire line section, and compare the theoretical calculations with experimental results. It is shown that the nonlinear regime can used successfully not only to measure plasma density, but plasma temperature as wall.

The basic scheme of the resonance microwave probe used in the experiments described below is shown in Fig. 1. Two equal coaxial cables end with magnetic coupling loops; a short-circuited end of a two-wire line section with its length l was placed symmetrically between them. At the other end the line is open. The distance between the wires, d, exceed their radius a significantly ($a/d << 1$) and coincides with the diameter of the coupling loops.

The inductance resistance of the coupling loops, $\frac{1}{c^2}\omega L_c$, is negligibly low as compared to the wave resistance of the coaxial cables, ρ_c. The coefficients of mutual inductance between the coupling loops ($M_{2,3}$), coupling loops and the two-wire line ($M_{2,1}$ and $M_{3,1}$) are close to L_c; moreover $M_{2,1} = M_{3,1} = M$, and the wave resistance of the two-wire line, ρ , is of the order of ρ_c. From above it follows that $\frac{1}{c^2}\omega L_c << \rho_c$, $\frac{1}{c^2}\omega M << \rho$. Behaviour of the current, $I(z)$, and voltage, $U(z)$, in long line 1 coordinate z is from its short-circuited end) can be described by means of telegraph equations:

$$\frac{dU}{dz} = -\frac{i}{c^2}\omega\tilde{L}\cdot I + E\,\delta(z+0), \quad \frac{dI}{dz} = -i\omega\tilde{C}U \quad (\,U(0)=0,\, I(z=\ell)=0), \qquad (1)$$

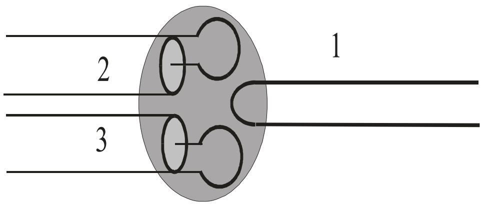

Fig.1. Quarter-wave resonator (1), exciting (2) and receiving (3) lines

where $\tilde{L}$ and $\tilde{C}$ are inductance and capacity of line 1 per unit length, respectively, $E = -\frac{i}{c^2}\omega M(I_2 + I_3)$ is e.m.f. of mutual induction concentrated near the short-circuited end ($z=0$), and $\delta(z)$ is delta function .

To diagnose plasma, researchers traditionally use frequencies ω, which exceed noticeably ω_{pe} and ω_{He} (ω_{pe} and ω_{He} are plasma frequency and gyrofrequency of electrons, respectively). In this case electrodynamic characteristics of the plasma differ little from the vacuum ones. In the long run one can assume that $\tilde{L} = \tilde{L}_0 \approx 4\ln(d/a)$, and $\tilde{C} = \tilde{C}_0(1+\delta C)$, $\tilde{C}_0 \approx \frac{1}{4\ln(d/a)}, |\delta C| << 1$ (here $\tilde{L}_0$ and $\tilde{C}_0$ are inductance and capacitance per unit length of line 1 in vacuum. In nonlinear media δC is determined by the field in the line and smoothly (on the scale of d) depends on the z coordinate.

In the presence of plasma the amplitude of the current in the line is defined by the coupling Q-factor, Q_0, and the following parameter: $q = \frac{1}{\ell}\int_0^{\ell} \delta C \sin^2(\frac{\pi z}{2\ell})dz$. Let us introduce the notion of the transmission coefficient, $\beta = \frac{|I_3|^2}{|I_0|^2}$. Using smallness of $|\delta C|$, one can easy obtain that

$$\beta == \frac{1}{\frac{1}{4}Q_0^2(\delta\omega + Re\,q)^2 + \left(1 + \frac{1}{2}Q_0\, Im\,q\right)^2}, \qquad (2)$$

where $\delta\omega = \frac{\omega - \omega_0}{\omega_0}, \omega_0 = \frac{\pi c}{2l}$.

In the case of collisionless plasma with its dielectric constant equal to $\varepsilon = 1 - \frac{N}{N_c}$, $N_c = \frac{\omega^2 m_e}{4\pi e^2}$ (where N is plasma density, m_e is electron mass, and e is electron charge), the influence of striction nonlinearity can be described by the following dependence of N on the intensity of the electric field, $\vec{E}\cdot e^{i\omega t}$: $N = N_0\, exp\left(-\frac{|\vec{E}|^2}{E_c^2}\right)$, where $E_c = \left(\frac{4(T_e+T_i)m_e\omega^2}{e^2}\right)^{1/2}$ is critical field of striction effects, T_e and T_i are electron and ion temperatures, respectively.

The characteristic parameter of striction nonlinearity looks as, $g_m = \frac{E_0^2}{E_c^2}$ (here E_0 is maximum value of the electric field on the surface of microwave resonator wires). *In the linear regime*, which is characterized by a small value of parameter g_m ($g_m << 1$), $N \approx N_0$ and $q \approx -\frac{1}{2}\frac{N_0}{N_c}$. In this case the shape of the resonance curve, $\beta(\omega)$, coincides with the vacuum one, but the curve *per se* moves as a whole along the frequency axis to the value of $\Delta\omega_m \approx \frac{1}{2}\frac{N_0}{N_c}\omega_0$. This correlation links the value of non-perturbed plasma density, N_0, and $\Delta\omega_m$. *Non-linear properties of the microwave resonator* caused by striction are manifested at $g_m > 1$. They lead only to displacement of the resonance curve but also to its deformation and, as result, to hysteresis phenomena.

The experiments often realize the situation, when frequency $\delta\omega$ is fixed, and the plasma density changes with time: e.g. becomes lower after the source generating it has been switched off. In this case it is more convenient to analyze dependencies $\beta(N)\big|_{\delta\omega=const}$ instead of resonance curves $\beta(\delta\omega)\big|_{N=const}$. It is easily seen that when g_m is within interval $1 < g_m < \left(\frac{3\Omega}{2\ln d/a}\right)^{1/2}$, $\Omega = \frac{Q_0}{2}\delta\omega$, then the following equation is valid, which links the bottom bifurcation value of $N_0 = N_b$ with g_m, and, hence, with plasma temperature:

$$\frac{Q_0 N_b}{4N_c} - \Omega \approx \left(\frac{3\Omega\ \ g_m}{2\ln d/a}\right)^{1/3}. \qquad (3)$$

The experimental setup was made as a vacuum chamber 3 m in diameter and 10 m long. The plasma was produced by means of an induction high-frequency breakdown (*f* = *5* MHz, $\tau_{имп} \approx$ 1.6 ms, $H_{\text{magn.f.}} \approx$ 200 Oe) in the argon atmosphere under the pressure of $5\ 10^{-4}$ Torr.

The experiments were performed in the regime of decaying plasma, i.e. after the high-frequency source had been switched off. The resonator of the microwave probe was made as a quarter-wave section of the two-wire line short-circuited at one end and open at the other. It was made of a copper silvered wire 8 mm long and 0.2 mm in diameter (the distance between the resonator wires was 2 mm). In the absence of plasma the minimum eigen-frequency of the resonator was f_0 = 8 GHz and its Q-factor was $Q_0 \approx 100$.

The oscillograms of the response of the resonance microwave probe at a low power level of the input signal were used to measure dependence on plasma density on time. Higher power fed to the microwave probe resulted in aberrations in the shape of its resonance responds. When plasma density reached some critical value (depending on the input power) a sharp increase in the output signal was observed with a consequent smooth decrease. As the input power was growing, the position of the step, $N=N_b$, shifted into denser plasma. The dependence of N_b on P was used to determine the electron temperature, T_e $(T_e >> T_i)$ by means of Eq. (3). Figure shows the results of measuring the temperature of electrons with a microwave probe and by means of a double probe. They agree well with each other.

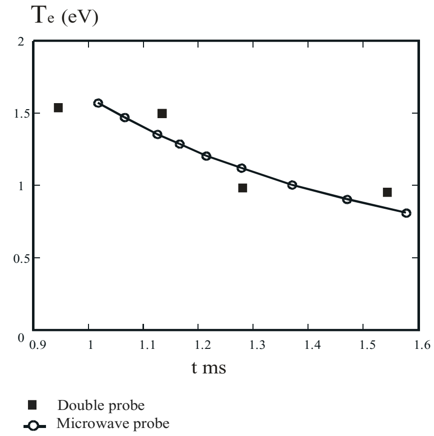

Fig.2. Results of measuring time dependence of the electron temperature obtained by means of a double probe and a microwave probe

Thus, the theoretical calculations of the nonlinear operation regime of the resonance microwave probe performed on a section of the two-wire line yield a rather adequate description of the experimental data, which makes it possible to use them for diagnostics of the electron temperature. The information about plasma density and its temperature obtained by means of the microwave probe under consideration agrees well with the results of the measurements performed with traditional single and double probes.

This research was supported by the Russian Foundation for Basic Research, projects No. 00-02-17321 and 01-02-16536.