MEASUREMENTS OF VERY SMALL PLASMA CONCENTRATION BY RF RESONATOR WITH PERIODIC SLOW WAVE STRUCTURE

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Necessity of contactless measuring small electron concentrations is actual, for example, in cosmic explorations, beam physics, electronics, etc. We found experimentally that the RF resonator with special periodic slow wave structure can measure n~10^5-10^8 cm^{-3}. The frequency of the resonator main mode is 628 MHz; Q=4500, phase velocity is $4.4 \cdot 10^9$ cm/sec. To determine the form-factor for this mode, an electron beam was passed through the resonator along its axis in vacuum of order of 10^{-6} Torr. The beam parameters were as following: energy 100 eV, current 1-10 mA, diameter 1 cm, that is corresponds to n~10^7-10^8 cm^{-3}. Measurement accuracy was about of 10 %. After the calibration, this resonator was used successfully for plasma density measurements that created by proton beam with energy 5 MeV at ionization of gases at pressure of 10^{-4}-10^{-5} Torr.
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The resonator (or cavity) method of plasma density measurements is used widely for plasma diagnostics in the range of n~10^8-10^{14} cm^{-3} (e.g., see [1, 2]). Unfortunately, the high frequency hollow cylindrical cavities that used in this method as the electron concentration n contactless pickup, do not allow to measure n<<10^8cm^{-3}. However, necessity of contactless measuring small electron concentrations is actual, for example, in cosmic explorations, beam physics, electronics, etc. The electron concentration in this case is as following:

$$n = \frac{2f^2}{10^8 F}\left(\frac{\Delta f}{f}\right), \qquad (1)$$

where the form-factor F is:

$$F = \int_{V_P} \vec{E}^2 dV \Big/ \int_{V_R} \vec{E}^2 dV . \qquad (2)$$

The minimum electron concentration is as following:

$$n_{\min} = \frac{2f^2}{10^8 F}\left(\frac{\Delta f}{f}\right)_{\min} \sim \frac{f^2}{10^9 FQ}, \qquad (3)$$

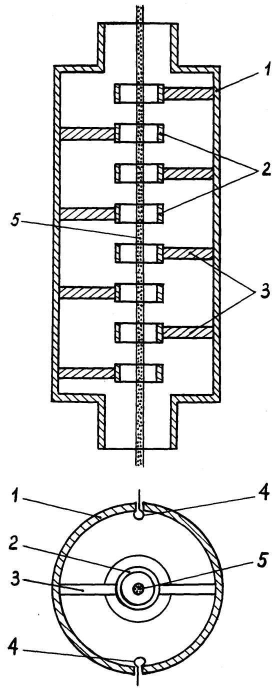
where it is supposed that

$$\left(\frac{\Delta f}{f}\right)_{\min} \sim \frac{1}{10Q}. \qquad (4)$$

Here f is the resonance frequency, Δf is the resonance frequency shift, Q is the resonance quality, F is the form-factor, E is the high frequency electric field, V_P is the plasma volume, and V_R is the cavity (or resonator) volume. Usually plasma is placed along the resonator axis, and the plasma radius is sufficiently less than the resonator radius. For usual parameters (f≈3 GHz, Q≈3000, F≈0.03, the resonator radius R≈10 cm) we have n≈10^8 cm^{-3}. To decrease n_{min} it need to increase the form-factor and decrease the resonator main frequency without increasing its radius.

We found experimentally that the RF resonator with special periodic slow wave structure (*PS*) can correspond to these conditions. In this case the periodic slow wave structure consists of ring RF electrodes fixed by interdigital suspenders, see Figure. (At the KIPT similar structures were proposed and used for ion linear accelerators [3,4]). Due to this geometry, the resonator main frequency decreases sufficiently, and the form-factor increases sufficiently as well, but the form-factor could not be find analytically.

To overcome this difficulty, we used the method of calibration based on the fact that a slow electron beam (with the velocity much less than the wave phase velocity) has the same high frequency properties as plasma [5]. The calibration by the electron beam was made for the different modes of the RF resonator without the periodic slow wave structure, and for the main mode of the RF resonator with the periodic slow wave structure.



Sketch of the resonator: 1-frame of the resonator, 2-ring RF electrodes, 3-suspenders, 4-RF coupling loops, 5-plasma column or electron beam

The experimental parameters are as it follows: the resonator length is 30 cm, its radius is 10 cm, the diameter and length of the ring electrodes are 3 cm and 1.8 cm, the distance between electrodes is 1.7 cm, the structure period is 7 cm. The frequency of the *RF* resonator main mode is 628 MHz; Q=4500, its phase velocity is $4.4 \cdot 10^9$ cm/sec. To determine the form-factor for this mode, an electron beam was passed through the resonator along its axis in vacuum of order of 10^{-6} Torr. The beam parameters were as following: energy 100 eV, current 1-10 mA, diameter 1 cm; that was corresponds to the electron concentrations

n~10^7-10^8 cm^{-3}. It was investigated also the same resonator but without the periodic structure. In that case the parameters were as follows: energy 1-10 keV, current 0.1-1 A, diameter 1 cm, that was corresponds to n~10^8-10^9 cm^{-3}, frequency range 1700-3800 MHz. For different modes, it was measured the resonator frequency shift versus electron beam current, and from (1) the form-factor F was determined. Measurement accuracy was about of 10 %. The results of measuring are presented in the Table.

Mode	Frequency, MHz	Form-factor (theory)	Form-factor (experiment)	Ranges of measurements, cm^{-3}
E_{010}, in cavity	2076	0.036	0.036	10^8-10^{10}
E_{012}, in cavity	2314	0.030	0.033	10^8-10^{10}
E_{013}, in cavity	2568	0.025	0.027	10^8-10^{10}
E_{014}, in cavity	2887	0.020	0.023	10^8-10^{10}
E_{015}, in cavity	3253	0.015	0.017	10^8-10^{10}
E_{016}, in cavity	3634	0.0090	0.0012	10^8-10^{10}
H_{011}, in cavity	3424	0.0011	0.0015	10^9-10^{10}
H_{211}, in cavity	2863	No	0.0003	10^9-10^{10}
H_{111}, in cavity	1750	No	0.03	10^8-10^{10}
H_{113}, in cavity	2195	No	0.035	10^8-10^{10}
H_{115}, in cavity	2898	No	0.025	10^8-10^{10}
Main, in resonator with *PS*	628	No	0.15	10^6-10^8

Conclusions from the measurements are as follows:

1) Experimental values of the form-factors coincide with theoretical ones that proof validity of the calibration procedure.
2) The frequency for the resonator with the periodic structure (*PS*) is over 3-4 times less than for the cavity with the same dimensions.
3) The form-factor for the resonator with *PS* is over 3-4 times grater than for that cavity.
4) The resonator with *PS*, used as the electron concentration n contactless pickup, allow to measure n_{min}~10^6 cm^{-3}, and even n_{min}~10^5 cm^{-3}, in case of additional conditions, particularly, using some methods of measuring small frequency shifts, e.g., [6].
5) Accuracy of the electron concentration measurements is about of 10 %.

After the calibration, this resonator was used successfully for measurements of plasma density that was created by proton beam with energy 5 MeV in case of ionization of gases at pressure of 10^{-5}-10^{-2} Torr: in that case the plasma density was varied in the range 10^6-10^9 cm^{-3}.

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ВИМІР ДУЖЕ МАЛИХ КОНЦЕНТРАЦІЙ ПЛАЗМИ ВЧ РЕЗОНАТОРОМ З ПЕРІОДИЧНОЮ УПОВІЛЬНЮЧОЮ СТРУКТУРОЮ

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Необхідність безконтактних вимірювань малих електронних концентрацій актуально, наприклад, для космічних досліджень, фізики пучків, електроніки і т.д. Для вимірювання малих електронних концентрацій нами запропонований ВЧ резонатор з уповільнюючою структурою, що складається з кільцевих ВЧ електродів, закріплених на зустрічних підвісках. Завдяки такій геометрії істотно збільшується форм-фактор резонатора, тобто коефіцієнт пропорційності між концентрацією і зсувом власної частоти. Проте, у даному випадку форм-фактор не може бути знайдений теоретично. Щоб перебороти цю трудність ми застосували метод калібрування, заснований на тому, що повільний електронний пучок має такі ж ВЧ властивості, як і плазма. Калібрування по електронному пучку була проведена для декількох мод полого резонатора і для основної моди резонатора з періодичною структурою. При цьому вимірювався зсув частоти резонатора в залежності від струму пучка, відкіля визначалися форм-фактори. Точність вимірювань була порядку 10%. Після такого калібрування цей резонатор був з успіхом застосований для вимірювання густини плазми, утворюваної протонним пучком з енергією 5 МеВ при іонізації газів при тиску 10^{-4} – 10^{-5} Торр.

ИЗМЕРЕНИЕ ОЧЕНЬ МАЛЫХ КОНЦЕНТРАЦИЙ ПЛАЗМЫ ВЧ РЕЗОНАТОРОМ С ПЕРИОДИЧЕСКОЙ ЗАМЕДЛЯЮЩЕЙ СТРУКТУРОЙ

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Необходимость бесконтактных измерений малых электронных концентраций актуально, например, для космических исследований, физики пучков, электроники и т.д. Для измерения малых электронных концентраций нами предложен ВЧ резонатор с замедляющей структурой, состоящий из кольцевых ВЧ электродов, закрепленных на встречных подвесках. Благодаря такой геометрии существенно увеличивается форм-фактор резонатора, т.е. коэффициент пропорциональности между концентрацией и сдвигом собственной частоты. Однако, в данном случае форм-фактор не может быть найден теоретически. Чтобы преодолеть эту трудность мы применили метод калибровки, основанный на том, что медленный электронный пучок имеет такие же ВЧ свойства, как и плазма. Калибровка по электронному пучку была проведена для нескольких мод полого резонатора и для основной моды резонатора с периодической структурой. При этом измерялся

сдвиг частоты резонатора в зависимости от тока пучка, откуда определялись форм-факторы. Точность измерений была порядка 10%. После такой калибровки этот резонатор был успешно применен для измерения плотности плазмы, создаваемой протонным пучком с энергией 5 МэВ при ионизации газов при давлении 10^{-4} – 10^{-5} Торр.