Hairpin-resonator probe design and measurement considerations

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Abstract. A hairpin-resonator probe is designed to measure the spatial distribution of the electron density in RF plasmas. An effective simulation procedure with the commercial software simulator Ansoft® High Frequency Structure Simulator 8 in eigen-mode option was applied to evaluate the influence of the resonator structures on the resonance frequency \( f_v \) and unloaded Q-factor \( Q_v \) of the resonance modes. Many geometrical constructions were examined and finally, an optimal modification is proposed.

1. Introduction

The hairpin probe is a simple microwave resonator successfully used for electron density measurements in low-pressure gas discharges. This type of plasma probe was introduced by Stenzel in 1976 [1]. Two modifications of the structure in “transmission” or “reflection” regimes have been discussed by Piejak et al. [2]. The transmission-type probe consists of a hairpin resonator, an input loop, and a pick-up loop, while the reflection-type probe includes only a coaxial cable with a magnetic loop at the end that feeds the hairpin structure. We use in our investigation a reflection-type hairpin resonator.

The considered hairpin probe is a quarter-wavelength two-wire resonator with one short-circuited end and one open end and resembles a “hairpin antenna”. The structure can be simply excited by a coaxial feed loop with a well-defined proximity to the short-circuited end. The resonant frequency of the hairpin antenna is related to the relative permittivity of the surrounding medium (vacuum or plasma). Therefore, the electron density can be accurately determined from the change between the resonance frequencies without (in vacuum) and with a low-pressure gas discharge. A theoretical analysis of the influence of the plasma sheath around the hairpin antenna has been performed in references [2, 3]. A detailed model of resonator plasma probe was reported in reference [4].

Recently, a number of papers have been published, which are dedicated to the design of different hairpin probes and give results from measurements of plasma parameters in low-pressure inductively-excited industrial plasmas with a variety of gas mixtures used for micro machining of micro devices for modern electronics and Micro-Electro-Mechanics (MEM) applications [5–8].

In this paper we describe experimental results about the hairpin design and its influence on the resonant frequency and return losses.
2. Design and measurement of hairpin probe in air

2.1. Hairpin resonator design and simulations

Outline of the used in the recent investigation hairpin antenna and its coupling with the GHz transmission/receiver coaxial cable is shown in figure 1. The spring section of the antenna wire allows an easy replacement of the hairpin antenna when it is necessary.

Figure 1. Outline of the mechanically stabilized hairpin with a wire spring section in the plasma probe.

The schematic view of the hairpin resonator and the 3D model for the resonator used in the commercial software simulator Ansoft® High Frequency Structure Simulator (HFSS) 8 in eigen-mode option is shown in figure 2. The wire thickness is \( t \), while the distance between the “hairpin” wires is \( W \).

Figure 2. Schematic view of the hairpin resonator wire with length \( L \) and cylindrical ceramic support and the 3D model of the resonator used in the Ansoft® HFSS simulator.

The simplest design of the hairpin resonator should be performed on the basis of the assumption for pure TEM-mode excitation in this structure. Therefore, the full hairpin length \( L \) should be equal to an integer number of quarter wavelengths \( \left( p\frac{\lambda_0}{4}; \lambda_0 \right. \text{ – wavelength} \) of the propagation mode in vacuum. In this case the simple expression for the resonator length \( L \)

\[
L, \text{mm} = p\frac{300}{4f_v}, \text{GHz}, \quad p = 1, 2, 3...
\]

(1)

is valid, where \( f_v \) is the work frequency of the hairpin probe in vacuum, and \( p \) is the mode number (usually \( p = 1 \)). Unfortunately, this simple analysis does not take into account the other dimensions of the resonator (e.g. \( W \) and \( t \)) and the influence of the ceramic support. Because of this, we additionally simulate this open-type resonance structure by the commercial software simulator Ansoft® HFSS-8 in eigen-mode option – see figure 2, in order to evaluate the influence of the other parameters on the resonance characteristics – the resonance frequency, \( (f_v)_0p \), and the unloaded Q-factor, \( (Q_v)_0p \), of the resonance modes in the hairpin resonator. Figure 3 presents the electric and magnetic field distribution of the first resonance \( TEM_{001} \) in the hairpin resonator with tungsten wires and alumina ceramic
support. Some results from the simulations are compared with the experimental data further on (see figure 7).

Figure 3. Electric-field and magnetic-field distribution of the first-order resonance obtained by HFSS-8 in eigen-mode option.

First of all, the software simulations show that a practical resonance structure, like this in figure 2, has lower resonance frequencies than those obtained by the simple expression (1). This effect is caused by two main reasons: the influence of the alumina ceramic support (with dielectric constant ~9.8) and the effective “prolonging” of the resonator length due to the so-called “fringing-field” effect in the E-field distribution near to the open resonator edge – see picture in figure 3. It is easy to show that the resonance frequency can be shifted mainly by the variation of the hairpin length $L$ – the resonance frequency decreases with the increase of $L$ ($-78$ MHz/mm of the resonator length), but the Q factor also decreases for longer resonators. The increase of the distance $W$ between the hairpin wires leads to a small decrease of the resonance frequency ($-2.2$ % for doubling of $W$). The thickness of the hairpin wires does not significantly affect the resonance frequency, but the Q factor strongly increases (for example, +41 % for doubling of $t$). A similar strong effect over the unloaded Q-factor increase is observed by increasing the wire conductivity (for example, with +36 % from tungsten $W$ to silver Ag), but the choice of the hairpin wire material depends on other reasons (for example, chemical resistance to the plasma gas mixtures).

2.2. Experimental hairpin probe and measurement results

The reflection-type hairpin probe is feed by a 50-Ohm coaxial cable with a coupling loop at one end a standard female SMA connector at the other end. The performances of the cable and the connector as well as the transition “connector-cable” between them are very important for the successful operation of the designed plasma probe. We have investigated many combinations between different commercial connectors and cables – soft, semi-flexible, semi-rigid and rigid. These structures are preliminary tested in Time-Domain Reflectometry (TDR) option (250 ns gate length) with a Vector Network Analyzer (VNA) Agilent 88720E. Then the results are converted into the Frequency-Domain (FD) option in a wide frequency range of 0–20 GHz. We have accepted the combinations for which the own return losses ($RL$) are smaller than $-25$ dB. This requirement will ensure a reproducible response from the hairpin probe at resonance frequencies in the range of 2.5 to 6 GHz.

Next step in the practical realization of the probe is the joining of the experimental hairpin resonator. We investigated several structures with different metal wires (tungsten, soft silver, silver-plated cooper, stainless steel, etc.) with practically equal wire diameter. The other differences in the experimental probes were the distance $W$ between the wires and finally the length $L$ of the each resonator simply controlled by cutting. Both structures, the coaxial feed line and the resonator, are designed to be independent components and we combined several structures to obtain the best
conditions. In this paper, we present a portion of these measurements only: for well-matched semi-flexible cable with female SMA connector and a hairpin resonator with cylindrical alumina ceramic support (diameter ~4 mm and length ~10 mm) with an overlapping between the coaxial input loop and the probe U-sector ~5 mm and with the following other parameters:

**Structure S1**: tungsten-wire probe with fixed length $L_1 = 25.5$ mm and fixed width $W_1 = 2$ mm;

**Structure S2**: tungsten-wire probe with different length $L_2 \sim 25.5 - 35$ mm and fixed width $W_2 = 4$ mm.

The length $L$ of the structure S2 is changed by cutting, keeping the distance $W$ between the wires.

### 2.3. Results and discussion

The variation of the resonance frequencies in air due to the change of the geometrical length of the hairpin wires is demonstrated in figure 4. It is easy to be shown that the resonance frequencies satisfy the simple equation for the fundamental frequency given in [9]. To the values of $L$ shown in figure 4 must be added about 5 mm for the length of the wires inside the ceramic body.

The data for the high-order modes show that the influence has more complicated character – there are also parasitic effects caused by a non-effective coupling at a given resonator length (a worsening of the resonance curves and even a vanishing of the resonance peak or the appearance of a lot of nearby parasitic resonance). Thus, an important question appears: which resonance of the hairpin resonator could be most suitable for gaseous plasma diagnostics? We recommend the frequency range below 5–6 GHz. In this range a simple and not very expensive measuring set-up could be realized.

When we measured the resonance structures in the reflection-signal option with a vector or scalar network analyzer, we observed a number of resonance curves in the $RL$ plot. Some of them are connected with the self resonances of the hairpin resonator. Unfortunately, we also have seen a lot of parasitic resonances, especially at higher frequencies, caused by the finite length of the feeding cable, coupling loop, etc. The parasitic resonances do not appear below 3 GHz. In contrast, above 6 GHz, a lot of parasitic resonances are observed and a reliable identification of the self (useful) resonances of the hairpin resonator could not be obtained. A metal cylindrical screen over the outer surface of the ceramic body of the structure could not considerably influence the self resonances, if its end is far enough from the coupling region (>10 mm). The coupling degree between the end of the transmission/receiver cable and the U shaped part of the antenna influences the resonance frequencies stronger (figure 5) compared with the case of other conventional semi-wavelength resonators.

**Figure 4.** Measured resonance curves of the return losses $RL$ in the structures S1 and S2.

**Figure 5.** Resonance-curve shift due to an accidental change of the coupling degree.

This is due to the fact that the change of the coupling loop distance to the short-ended part of the hairpin resonator modifies the effective resonator length, and therefore it changes the resonance frequency. The frequency shift is only ~60–70 MHz at 5.7 GHz, but this shift may affect the
preliminary calibration of the resonance structure. From now on, we focused our considerations over the resonances in the considered structures S1 below 6 GHz.

At the curve minimum, where the return losses are $L_r$ (dB), we determine the resonance frequency $f_v$ in vacuum. The corresponding loaded Q factor $Q_{Lv}$ is calculated by the expression $Q_{Lv} = f_v / \Delta f$, where

Figure 6a. Wide-band reflection response of the hairpin structure with three excited resonances. Figure 6b. Narrow-band response of $TEM_{002}$ mode: $f_v \sim 5700$ MHz, $\Delta f \sim 30$ MHz, $Q_{Lv} \sim 190$, $Q_{0v} \sim 211$.

the resonance line-width $\Delta f$ is determined at level $L_r + 3$ dB of the return losses. Finally, the unloaded Q factor $Q_{0v}$ can determine by the expression

$$Q_{0v} = \frac{Q_{Lv}}{1 - 10^{-|L_r|/20}}$$

At one most effective coupling we have measured three resonance frequencies for structure S1. The corresponding Q-factors were as follows: 1) $TEM_{001}$ mode: $f_v = 2127.5$ MHz with loaded Q-factor $Q_{Lv} \sim 61$ (unloaded $Q_{0v} \sim 79$); 2) $TEM_{002}$ mode: $f_v = 5700$ MHz, $Q_{Lv} \sim 190$ ($Q_{0v} \sim 211$); 3) $TEM_{003}$ mode: $f_v = 9490$, $Q_{Lv} \sim 158$ ($Q_{0v} \sim 176$). The first two resonances are well excited and without nearby parasitic resonances. Their Q-factors are high enough for similar open-type resonators as the hairpin. The resonances curve of the third mode is partially masked by a nearby parasitic resonance and the Q factor is not high enough. We conclude that the control of the plasma parameters should be performed on both low-order resonances ($TEM_{001}$ and $TEM_{002}$ modes).

Figure 7a. Dependencies of the resonance frequencies of structures S1 and S2 versus the wire length $L$. Figure 7b. Dependencies of the unloaded ($Q_{0v}$) and loaded ($Q_{Lv}$) Q-factors versus the wire length $L$. 

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Figure 7 (a-b) illustrates the measured and the HFSS-simulated influence of the length of the hairpin wires over the resonance frequency and the unloaded Q-factor of the $TEM_{001}$ mode for structure S1 and S2.). The decrease of the length of the structure shifts linearly the resonance frequency of the $TEM_{001}$ mode to higher values (~ 52 MHz/1 mm). The loaded (measured) Q-factor also changes with the wire length, but changes are relatively small. The comparison between the measured and the simulated resonance frequencies is very good. Unfortunately, the simulated unloaded Q-factor is 2 to 4 times greater due to many reasons. The most important reason is that, we cannot determine well the actual value of the surface resistance of the metal wires due to the poor surface cleanness, oxidation, roughness, temperature change, etc. Thus, the HFSS simulations for the Q factor are only informative for the probe performance.

In the final case (figure 7b), we compare the parameters of the both structures S1 and S2 with fixed length 25.5 mm and different width between the wire ~2 and 4 mm. The narrow hairpin resonator has better performance: resonance frequency ~2.72 GHz and unloaded $Q_0$ factor 106, while the wide resonator shows worse parameters: resonance frequency ~2.41 GHz and unloaded $Q_0$ factor 60.

3. Conclusions
An effective simulation procedure with the commercial software simulator Ansoft® High Frequency Structure Simulator 8 in eigen-mode option can be applied to evaluate the influence of the resonator structures on the resonance frequency ($f_v$)$_{00p}$ and unloaded Q-factor ($Q_v$)$_{00p}$ of the resonance modes. The coupling between the U shaped hairpin antenna and the transmitter/receiver end of the coaxial cable is essential for reliable and repeatable measurements of the electrons density in RF plasma chambers.

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