CAVITY TUNING EXPERIMENTS WITH THE JYFL 14 GHz ECRIS *

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Abstract

Experimental results showing the effect of cavity tuning on oxygen beam currents extracted from the AECR-type JYFL 14 GHz ECRIS are reported. The microwave-plasma coupling properties of the ion source were adjusted by inserting a conducting tuner stub through the injection plug, thus changing the dimensions of the plasma chamber and affecting the cavity properties of the system. The beam currents of high charge state ions were observed to vary up to some tens of percent depending on the tuner position and the microwave frequency. In this paper we focus on reporting results obtained in the frequency range of 10.75–12.75 GHz.

INTRODUCTION

Experiments with 2nd generation ECR ion sources have demonstrated that the beam currents of high charge state ions are sometimes sensitive to microwave frequency variations on the order of 10 MHz [1, 2]. The effect has been ascribed to frequency dependent electromagnetic field pattern over the resonance surface [3,4], i.e. excitation of cavity modes, and named frequency tuning effect (FTE). This explanation, however, has two significant shortcomings: (1) the electromagnetic properties of the cavity are strongly affected by the plasma [5], thus obscuring the mode structure, and (2) only Caprice-type ion sources [6] exhibit strong frequency dependence while the performances of A-ECR type sources [7] are less sensitive to FTE. The most significant difference between the two source types is the microwave coupling scheme. In Caprice-type sources the microwave power is launched into the plasma chamber through an external waveguide-to-coaxial transition component equipped with a stub tuner for impedance matching. In the AECR-type sources the microwave-plasma coupling is realized through a waveguide port inserted directly into the plasma chamber, hence making the A-ECR design less complex. These microwave coupling structures are presented in Fig. 1 [8].

It can be argued that the observed differences between the source types could be explained solely by the sensitivity of the microwave-plasma coupling system on the frequency variations, not by the excitation of cavity modes. Thus, probing the source performance by varying the frequency of the microwave radiation is not the optimal technique to detect the existence of possible cavity modes and to study their effect on the high charge state ion beams. This is because both, the microwave launching system and the (possible) cavity modes are sensitive to frequency variations. The cavity modes and their Q-values are determined by the dimensions and surface properties of the plasma chamber. Thus, a preferred technique to probe the existence of the cavity modes and their influence on the source performance is to change the dimensions of the plasma chamber while keeping the microwave frequency constant. Such experiments probing the *cavity tuning effect* (CTE) of an A-ECR-type ion source operating in the frequency range of 14.00–14.15 GHz have been reported recently [9]. It was shown that the extracted currents of the high charge state ions can be increased only moderately (<10 % for O^{6+}) by tuning the cavity properties of the plasma chamber. Since the frquency range probed in Ref. [9] is rather narrow, the CTE was studied further in a wider range of frequencies as described in the following sections.

EXPERIMENTAL SETUP

The experimental data discussed hereafter were taken with the JYFL 14 GHz ECRIS [10] (see Fig. 2), which is a typical A-ECR-type room-temperature ion source. The plasma chamber of the JYFL 14 GHz ECRIS has an inner diameter of 76.2 mm and length of 278 mm and is made of aluminum. The cylindrical symmetry of the chamber is broken by two waveguide ports (WR62 and WR75) and radial pumping holes between each magnetic pole of the sextupole. Furthermore, the cavity properties are affected by ϕ =21 mm biased disc and ϕ =8 mm plasma electrode aperture. In the present study the cavity dimensions were modified by inserting a cylindrical (ϕ =15 mm) water-cooled copper rod shown in Fig. 2 into the plasma chamber through the opening in the injection plug, normally used as a port for a miniature oven. The rod was connected electrically to the plasma chamber and its position was adjusted online by using a linear feedthrough without compromising the vacuum or switching off the microwave power or the high voltage while monitoring the extracted beam currents. The rod position was varied from 0 mm, corresponding to the

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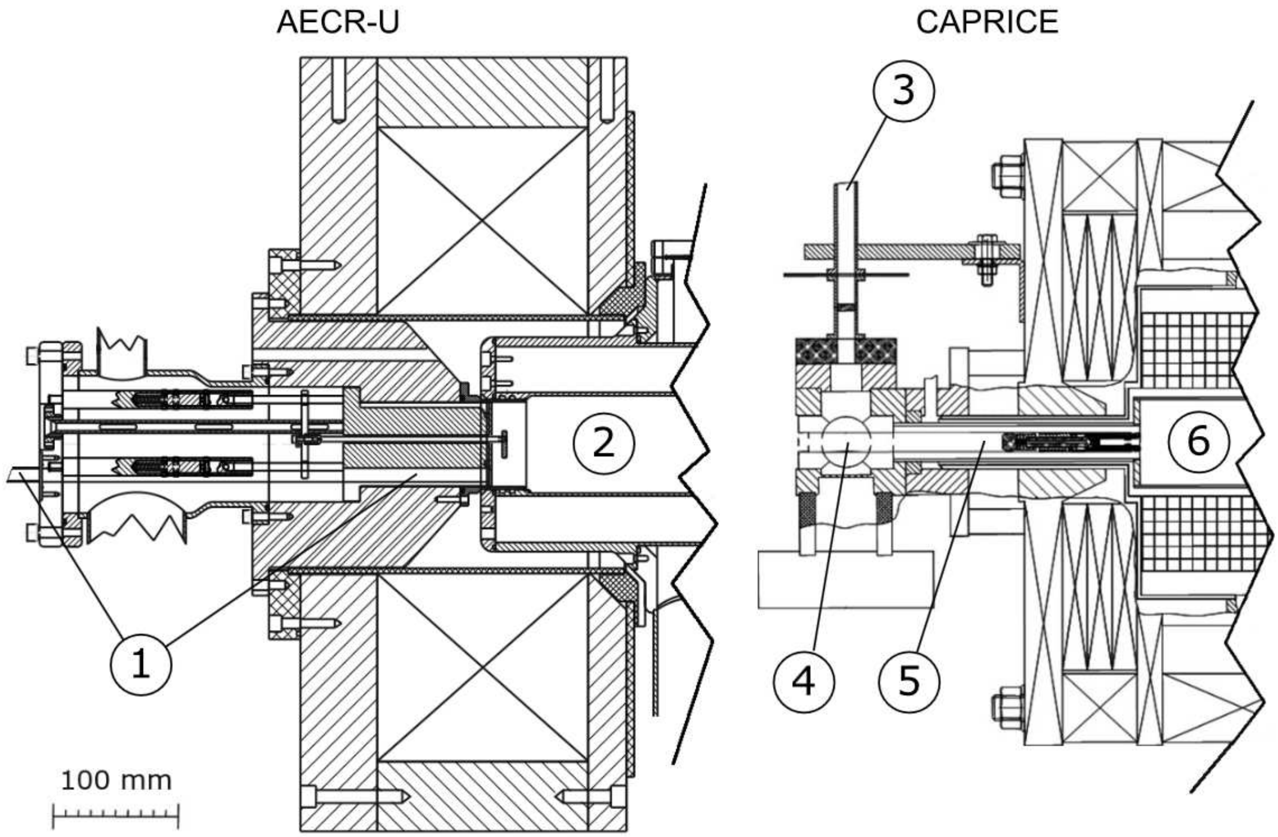

Figure 1: Comparison of the microwave coupling schemes of JYFL 14 GHz AECR-U and GSI Caprice ECR ion sources. AECR-U: (1) rectangular waveguide (WR62 / WR75), (2) plasma chamber. Caprice: (3) rectangular waveguide, (4) tunable matching cavity, (5) coaxial transmission line, (6) plasma chamber. The figure is borrowed from Ref. [8].

tip of the rod being aligned with the plane defined by the plasma facing surface of the biased disc, to 50 mm corresponding to the rod being inserted further into the plasma chamber. It was observed that the tip of the tuner rod was in contact with one of the plasma flutes at a distance of 60 mm and, therefore, the linear motion of the rod was restricted to 50 mm where no outgassing from the rod surface was observed. The arrangement allows tuning the cavity properties without affecting plasma losses or the magnetic mirror ratios.

The cavity properties were initially studied experimentally with a Rohde&Schwarz 9 kHz–15 GHz vector network analyzer that was used for measuring the output return loss, hereafter referred as the S11-parameter, of the waveguide system in the frequency range of 10.75–12.75 GHz corresponding to the bandwidth of the TWT amplifier connected to the WR75 port. The effect of the tuner position on the S11-parameter was first studied with an empty cavity. The experiment was then repeated with the ECR plasma being sustained by microwave radiation (at 14.053 GHz) provided by the klystron amplifier connected to the WR62 waveguide port. In this experiment the network analyzer connected to the TWTA waveguide (WR75 port) was protected from transmitted power with a low-pass filter. The power applied for sustaining the plasma was varied and the effect of the tuner position on the S11-parameter within the TWTA bandwidth was studied at different microwave powers presumably corresponding to different plasma densities. Measurement of the S11-parameter allowed distinguishing certain frequencies of interest, which were then used in the experiments studying the effect of the tuner position on the extracted beam currents of oxygen charge states O^{3+} – O^{7+} in single frequency heating mode with the TWTA. The beam currents were measured from a Faraday cup located downstream from a 90 degree m/q-analyzing magnet. The source potential was set to 10 kV, which is a typical value for the operation of the JYFL 14 GHz ECRIS. The currents of O^{+} and O^{2+} were not measured because their magnetic rigidity, resulting from the 10 kV source potential, is too high for these charge states to be transported through the bending magnet. On the other hand decreasing the source potential is not desired as the transport efficiency of the low energy beamline would become rather poor at values $\leq$ 7.5 kV potentially skewing the results. Since the parameter space of ECRIS optimization is extensive, the microwave power, oxygen feed rate and biased disc voltage were kept constant throughout the experiment. The (solenoid) magnetic field strength was optimized for each microwave frequency with the tuner fully retracted (at 0 mm) and then kept constant while moving the tuner inwards.

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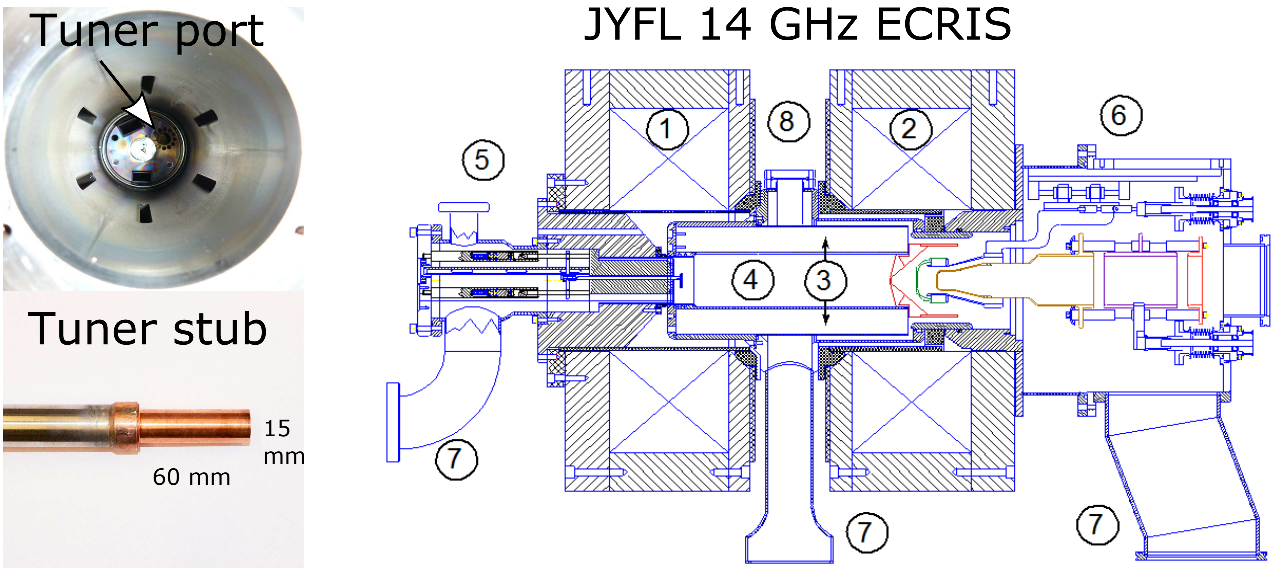

Figure 2: The JYFL 14 GHz ECRIS and the tuner used in the cavity tuning experiments: (1) injection coil (2) extraction coil (3) permanent magnet sextupole (4) plasma chamber (5) iron plug, biased disc, waveguide ports and oven (tuner) port, (6) extraction system, (7) vacuum pumping and (8) radial port (vacuum gauge). The location of the tuner port is shown in the upper left subfigure where the injection plug of the ECRIS is viewed from the extraction.

EXPERIMENTAL RESULTS

The Effect of Cavity Tuning on the S11-Parameter

Figure 3 is an example showing the empty cavity S11-parameter measured from the WR75 port (including the plasma chamber, vacuum window, high voltage break and short section of the waveguide) as a function of the tuner position in a narrow microwave frequency range of 11.70–11.85 GHz. The periodic ripple that is practically immune to the tuner position and dominates the frequency response of the S11-parameter is due to excitation of waveguide modes. The tuner effect is responsible for the seemingly random variation superimposed on the periodic structure, best observed at approximately 11.76 and 11.83 GHz. The implication of Fig. 3 is that studying the excitation of cavity modes and the subsequent effect on the electron heating by varying only the frequency is virtually impossible due to the dominance of the waveguide system.

The presence of the plasma affects the cavity behavior significantly as demonstrated in Fig. 4 showing the S11-parameter as a function of the tuner position at 11.70–11.85 GHz with the plasma sustained by 100 W power at 14.053 GHz. It was observed that already at 2 W of power from the klystron was sufficient to suppress the effect of the tuner position on the S11-parameter. The value of the S11-parameter at each frequency is defined by the combined effect of the short waveguide section, vacuum window, high voltage break and the plasma chamber. However, it is clearly seen that the presence of the plasma obscures the S11-behavior observed with the empty cavity. In the presence of the plasma the number of the S11-parameter minima in the given frequency range is determined by the length of the remaining waveguide i.e. the influence of the cavity is

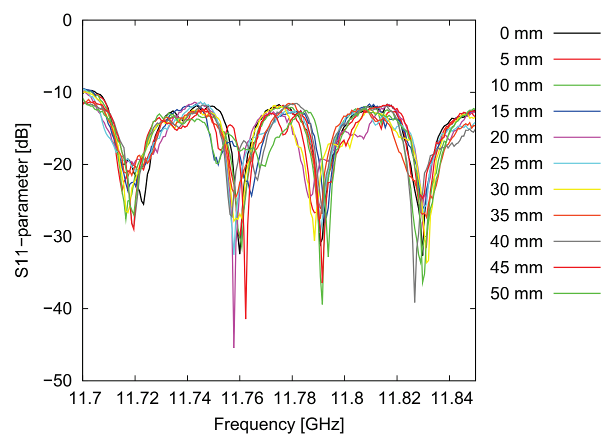

Figure 3: The empty cavity S11-parameter as a function of the microwave frequency at several tuner positions.

effectively suppressed. Although Figs. 3 and 4 only demonstrate the effect of the plasma in a narrow frequency range, similar observation was made for the complete frequency range of the TWTA.

The Effect of Cavity Tuning on Oxygen Beam Currents

The effect of the tuner position on the extracted currents of different charge states of oxygen was studied at several frequencies within the range of 10.75–12.75 GHz. The frequencies were chosen based on the measurement of the S11-parameter i.e. the m/q-spectra were recorded at those frequencies where the empty cavity S11-parameter was observed to be sensitive to the tuner position throughout the adjustment range of the tuner.

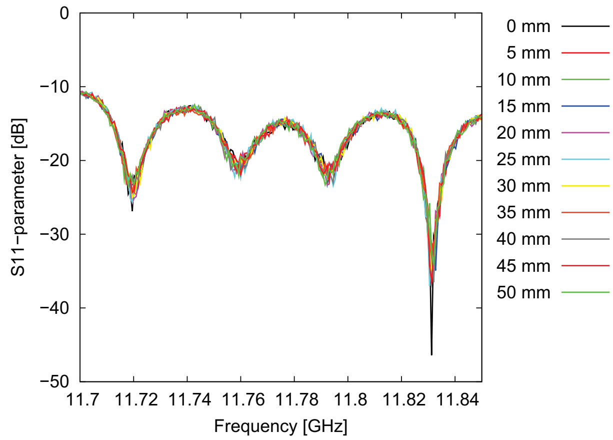

Figure 4: The S11-parameter in the presence of the plasma, sustained by 100 W power at 14.053 GHz, as a a function of the microwave frequency at several tuner positions.

Figure 5 shows the recorded m/q-spectra at 11.56 GHz. The microwave power was kept constant at 150 W (typical for the TWTA operation of the JYFL 14 GHz ECRIS) while all the other source parameters, i.e. magnetic field, gas pressure, bias disc voltage and extraction optics were first optimized for the charge state O^{6+} with the tuner at 0 mm. The data were chosen for display because they represent the frequency at which the source performance was found to be most sensitive to the tuner position within the studied range. Three different m/q-spectra are shown - the tuner fully retracted (0 mm), and at tuner positions corresponding to minimum and maximum O^{6+} current obtained at the given frequency. It is clear from the figure that the tuner position affects the charge state distribution.

The (temporally averaged) O^{6+} currents obtained at each studied frequency and tuner position are displayed in Fig. 6. It can be seen that the O^{6+} current is affected at all frequencies by several tens of percent depending on the tuner position. At 11.56 GHz the current was observed to vary +15 / –40 % in comparison to the baseline (tuner at 0 mm). This is partially explained by the fact that varying the tuner position makes the plasma prone seemingly arbitrary hopping between two modes at irregular intervals, which can suppress the average currents of the high charge states by several tens of percent. It was observed that the susceptibility of the plasma to the 'mode-hopping' depends on the frequency. For example, at 10.91 GHz there were no signs of the phenomenon while at 11.56 GHz mode transitions were observed consistently with the tuner positions of 25–35 mm and 45–50 mm, which explains the large (up to 40,%) variation of the high charge state currents in the latter case.

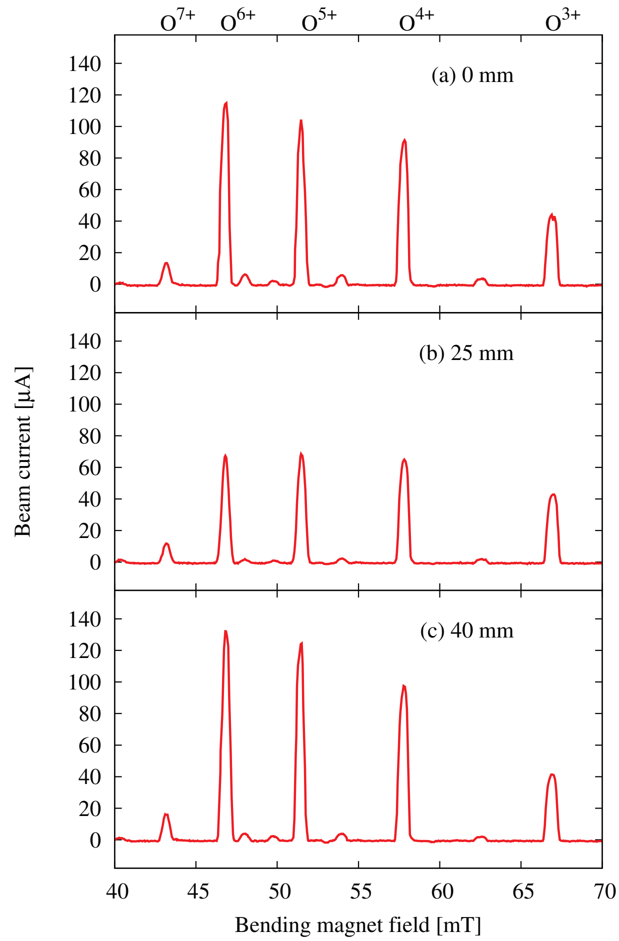

Figure 5: The m/q-spectrum of oxygen recorded with 150 W at 11.56 GHz at the tuner positions of (a) 0 mm with 115 µA of O^{6+}, (b) 25 mm with 69 µA of O^{6+} (minimum) and (c) 40 mm with 132 µA of O^{6+} (maximum).

DISCUSSION

The experimental results and conclusions can be summarized as follows:

- The charge state distribution of extracted oxygen beam can be affected by the tuner position.
- The optimum tuner position depends on the microwave frequency.
- The extracted currents of the high charge state ions can be increased moderately (≥20 % for O^{6+}) in comparison to the baseline, i.e. tuner at 0 mm, by optimizing the tuner position when operating in the frequency range of 10.75 – 12.75 GHz.
- Varying the tuner position makes the plasma prone to being unstable, which explains the shift of the charge state distibution in some cases.
- The S11-parameter can not be considered as a good indicator of the source performance as a function of the tuner position. The presence of the plasma even at low density makes the S11-parameter insensitive to the tuner position although the tuner clearly affects the charge state distribution.

The experimental results and conclusions are largely similar to those reported in Ref. [9] for the (klystron) frequency

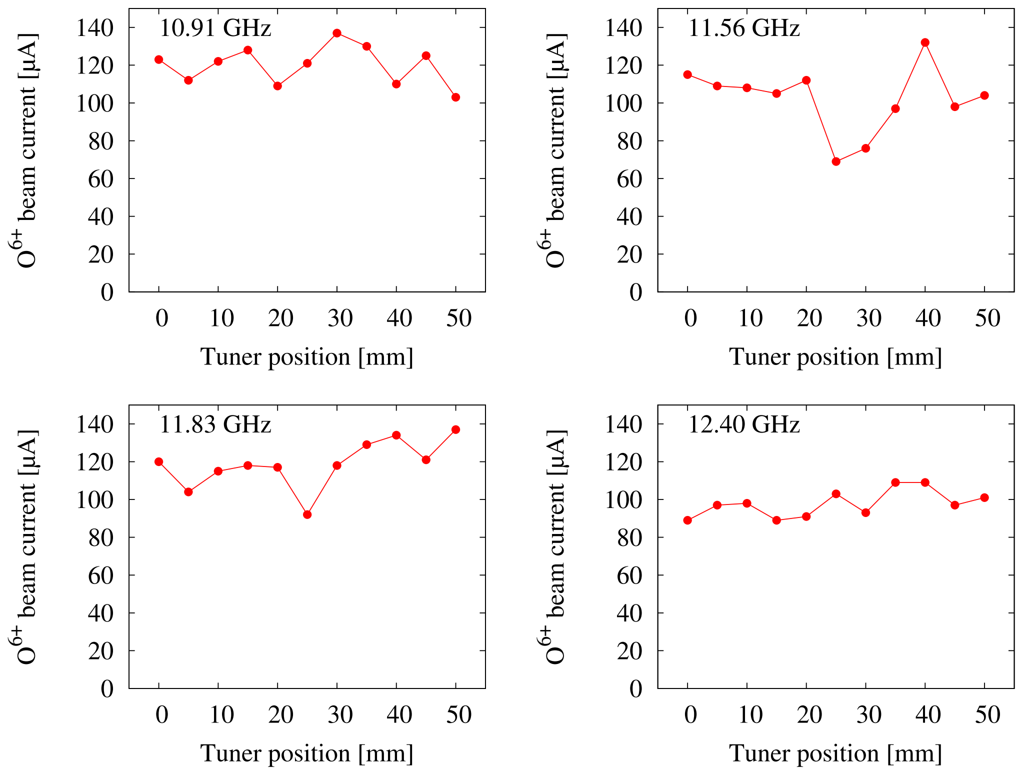

Figure 6: Temporally averaged O^{6+} beam currents as a function of the tuner position at different microwave frequencies with 150 W power.

range of 14.00–14.15 GHz. The variation of the high charge state beam currents (e.g. O^{6+}) was found to be more significant in operation with the TWTA at 10.75–12.75 GHz. This is probably be due to lower power (plasma density) operation with the TWTA with approximately 150 W maximum power across the frequency band. At lower power even a small change in the microwave-plasma coupling efficiency could drastically change the source performance whereas at high power the extracted beam currents of the JYFL 14 GHz ECRIS tend to saturate and, therefore, variations of the coupling efficiency are not as pronounced. It is, nevertheless, concluded that cavity tuning affects the plasma properties of the ECRIS. This is most likely due to modified electric field structure.

It must be emphasized that the ECRIS plasma is a dynamic load, i.e. the electric field configuration is affected by the plasma properties, which are driven by the electron heating (electric field) and ionization (neutral gas density and species). Thus, it could be expected that attempts to optimize the source performance by optimizing the electric field configuration (cavity mode) would inevitably result to unstable operation due to strong feedback loop. As already described, such mode-hopping effect was observed for certain frequency / tuner position combinations. Furthermore, it was demonstarted that the S11-parameter is not a good measure for the source performance and should not be used for probing the frequency response of the microwave-plasma coupling.

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