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The effect of cavity tuning on oxygen beam currents of an A-ECR type 14 GHz electron cyclotron resonance ion source

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The effect of cavity tuning on oxygen beam currents of an A-ECR type 14 GHz electron cyclotron resonance ion source

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The efficiency of the microwave-plasma coupling plays a significant role in the production of highly charged ion beams with electron cyclotron resonance ion sources (ECRISs). The coupling properties are affected by the mechanical design of the ion source plasma chamber and microwave launching system, as well as damping of the microwave electric field by the plasma. Several experiments attempting to optimize the microwave-plasma coupling characteristics by fine-tuning the frequency of the injected microwaves have been conducted with varying degrees of success. The inherent difficulty in interpretation of the frequency tuning results is that the effects of microwave coupling system and the cavity behavior of the plasma chamber cannot be separated. A preferable approach to study the effect of the cavity properties of the plasma chamber on extracted beam currents is to adjust the cavity dimensions. The results of such cavity tuning experiments conducted with the JYFL 14 GHz ECRIS are reported here. The cavity properties were adjusted by inserting a conducting tuner rod axially into the plasma chamber. The extracted beam currents of oxygen charge states O^{3+} – O^{7+} were recorded at various tuner positions and frequencies in the range of 14.00–14.15 GHz. It was observed that the tuner position affects the beam currents of high charge state ions up to several tens of percent. In particular, it was found that at some tuner position / frequency combinations the plasma exhibited “mode-hopping” between two operating regimes. The results improve the understanding of the role of plasma chamber cavity properties on ECRIS performances. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4962026>]

I. INTRODUCTION

In minimum-B electron cyclotron resonance ion sources¹ (ECRISs), highly charged ions are produced by electron impact ionization in magnetically confined plasma sustained by microwave radiation. It has been observed that the performance of an ECRIS scales with the microwave frequency as $I^q \propto \omega_{rf}^2$, where I^q is the extracted beam current at the peak of the charge state distribution and ω_{rf} is the (angular) frequency of the microwaves.² It is therefore seemingly straightforward to make advances in the ion source technology since powerful gyrotron-based microwave generators with frequencies up to 170 GHz are commercially available.³ However, the nature of the electron heating and plasma confinement prohibits using such approach. Resonant electron heating occurs when the electron gyrofrequency, ω_{ce} , in the ECRIS magnetic field matches the microwave frequency, i.e., $\omega_{ce} = \omega_{rf}$. Since the electron gyrofrequency depends on the external magnetic field, $\omega_{ce} \propto B$, increasing the microwave frequency inherently implies that the required magnetic field strength increases as well. Furthermore, according to semiempirical scaling laws of the ECRIS magnetic field,⁴ efficient plasma confinement

requires the local maximum magnetic field at the boundaries of the plasma chamber to be 2–4 times the resonance field. State of the art minimum-B ECRISs such as VENUS⁵ at LBNL operate with 28 GHz microwave radiation, which translates to a resonance field of 1 T, and implies that the maximum field strength in the plasma chamber reaches 4 T. Hence, the latest generation of minimum-B ECRISs typically relies on superconducting magnet technologies, which inevitably makes further development of the ion sources time-consuming, expensive, and rigid in terms of testing innovative ideas.^{6,7}

In order to avoid the looming stagnation of the ECRIS development and performance, numerous methods have been introduced to boost the production of highly charged ions. Those in regular use include gas mixing, biased disc, optimization of the plasma chamber surface material, and multiple frequency heating.^{8,9} A promising newcomer in this “collection of techniques” is the so-called frequency tuning effect (FTE).¹⁰ Experiments with some 2nd generation ECR ion sources have demonstrated that the extracted beam currents are sensitive to microwave frequency variations on the order of 10 MHz.^{10,11} It has been argued¹² that the beam current variations associated with the minute frequency shifts are due to the excitation of electromagnetic eigenmodes of the plasma chamber acting as a resonator cavity, and subsequent differences between the electron heating properties that presumably affect

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the ionization rate and plasma confinement, as well as ion dynamics.¹³ Nevertheless, there are apparent complications in this explanation in the light of published data.

First of all, the plasma unquestionably affects the electromagnetic properties of the cavity through absorption of the microwave radiation, therefore obscuring the cavity modes.¹⁴ Secondly, the FTE is hardly observed with all ion sources. There are two types of 2nd generation ECR ion source designs, i.e., the Caprice-type¹⁵ and AECR-type.¹⁶ The performance of the Caprice-type ion sources typically exhibits strong frequency dependence^{10,11} while the AECR-type sources have been observed^{17,18} to be less sensitive to fine tuning of the frequency in ~ 100 MHz frequency bands typical for klystron-type microwave amplifiers. The main differences between the two source types are the plasma chamber dimensions and microwave-plasma coupling scheme. The radius of the Caprice-type source plasma chamber is typically $\sim 15\%$ smaller in comparison to the A-ECR-type source, which affects the distribution of the cavity modes in frequency domain. The smaller plasma chamber allows larger separation of the modes and could prevent their overlap when the plasma is ignited. A more 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 which is adjusted to a certain position for proper impedance matching. In the AECR-type sources, the microwave coupling is realized through a waveguide port inserted directly into the plasma chamber, which makes the A-ECR design less complex. A thorough comparison of the coupling schemes can be found in Ref. 19.

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. Here “system” refers to the entire microwave launching setup including the waveguide, vacuum window, high voltage break, and adapters. It has been, for example, observed that the excitation of waveguide (not cavity) modes can explain the fine structure of frequency response of the beam current extracted from an A-ECR type ion source within a certain frequency range.¹⁸ 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 beam production. 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 cavity while keeping the microwave frequency constant. Such experiments probing the *cavity tuning effect* (CTE) of an A-ECR-type ion source are reported in this paper.

To our knowledge this is the first systematic study of the CTE, although experiments in which the cavity dimensions were changed either by moving the plasma electrode²⁰ or the biased disc²¹ or by installing sputter samples²² or so-called collars of varying dimensions around the extraction aperture²³

have been reported. Those experiments, however, were either not focused on the cavity tuning effect or required exposing the ion source to atmospheric pressure between different data points, thus, complicating the interpretation of the results. Furthermore, in the experiments in which the cavity dimensions were changed by moving the plasma electrode or the biased disc the plasma confinement properties were inevitably affected. This is because the ends of the plasma chamber, where the plasma flux is in contact with conducting material, were moved with respect to the magnetic field. Nevertheless, it was observed, for example, with the movable biased disc that the extracted currents of highly charged ions varied up to 50% depending on the position of the disc²¹ providing further motivation for the present work.

II. EXPERIMENTAL SETUP AND PROCEDURE

The experimental data discussed hereafter were taken with the JYFL 14 GHz ECRIS,²⁴ which is a typical A-ECR-type room-temperature ion source. A comprehensive description and schematic drawings of the ion source including the latest upgrades of the magnetic field configuration can be found from Ref. 27.

The JYFL 14 GHz ECRIS is equipped with two rectangular waveguide ports reaching directly into the plasma chamber through the injection iron plug as shown in Fig. 1(a). The WR-62 port (at six o’clock) is used for the injection of the primary microwave power at a certain frequency within the bandwidth of the klystron-type amplifier (nominally 14.053 GHz). The waveguide assembly connecting the klystron to the ECRIS consists of the following components: WR-62 to WR-75 adapter, WR-75 waveguide (several meters), high voltage break, WR-75 to WR-62 adapter, vacuum window, and finally a short (~ 0.5 m) WR-62 waveguide reaching into the plasma chamber. The WR-75 port (at eleven o’clock) is used for the injection of 10.75–12.75 GHz microwaves from a traveling wave tube amplifier (TWTA) in double frequency heating mode. 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 the waveguide ports (shown in Fig. 1(a)) and radial pumping holes between each magnetic pole of the sextupole. Furthermore, the cavity properties are affected by

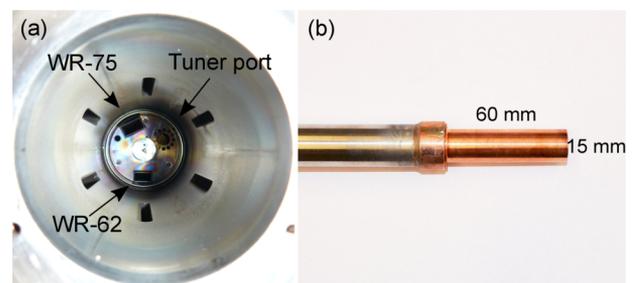


FIG. 1. (a) The injection end of the JYFL 14 GHz ECRIS plasma chamber viewed from the extraction. The waveguide ports and the oven port used for inserting the tuner are identified in the figure. The biased disc can be seen on the axis. (b) The $\phi = 15$ mm copper tuner rod inserted into the plasma chamber through the oven port.

a $\phi = 21$ mm biased disc and a $\phi = 8$ mm plasma electrode aperture. The cavity dimensions were modified by inserting a cylindrical ($\phi = 15$ mm) water-cooled copper rod shown in Fig. 1(b) into the plasma chamber through the opening (at two o'clock in Fig. 1(a)) in the injection plug, normally used as a port for a miniature oven. The shape, size, and radial position of the tuner are dictated by the dimensions of the opening in the injection plug. 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 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. The zero position of the tuner corresponds to the regular position of the miniature oven, which is used not only for metal ion beam production but also for preventing microwave leakage through the opening shown in Fig. 1. 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, which is an apparent limitation with the movable plasma electrode²⁰ or biased disc.²¹

The effect of the tuner position on the cavity properties was first studied with simulations with CST Microwave Studio²⁵ assuring that the tuner position affects the electric field distribution and strength of an empty cavity. This is demonstrated in Fig. 2 showing the rms electric field at three tuner

positions, namely 0, 25 and 50 mm, at the plane crossing the axes of the plasma chamber and the tuner. The simulated electric field distribution with the tuner at 25 mm deviates evidently from the field distributions obtained with the tuner either completely retracted (0 mm) or inserted (50 mm). The microwave frequency used in the given example is 14.053 GHz, which is one of the frequencies used later in the experiments. The effect of the microwave frequency on the electric field distribution and strength was found to be less pronounced in comparison to the effect of the tuner position. The simulation was conducted with an input (rms) power of 0.5 W and all essential features, i.e., biased disc, waveguides, and extraction aperture, of the plasma chamber were taken into account. The simulation should be treated only as an indication of the tuner affecting the cavity properties without the presence of the plasma, which (when ignited) inevitably changes the electric field strength and distribution.

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 the klystron, i.e., 14.00–14.15 GHz. The contribution of the waveguide system and the cavity (plasma chamber) was distinguished by connecting the network analyzer to two positions; close to the klystron, i.e., at the end of the waveguide assembly, and close to the plasma chamber between the high voltage and vacuum breaks, and finally comparing the results. A coaxial microwave cable (1.5 m) and coaxial-to-waveguide adapter were used for the connection. Their influence on the S11-parameter was not calibrated since the purpose of the following experiments was to study the effect of the tuner position, i.e., only relative changes of the frequency response of the

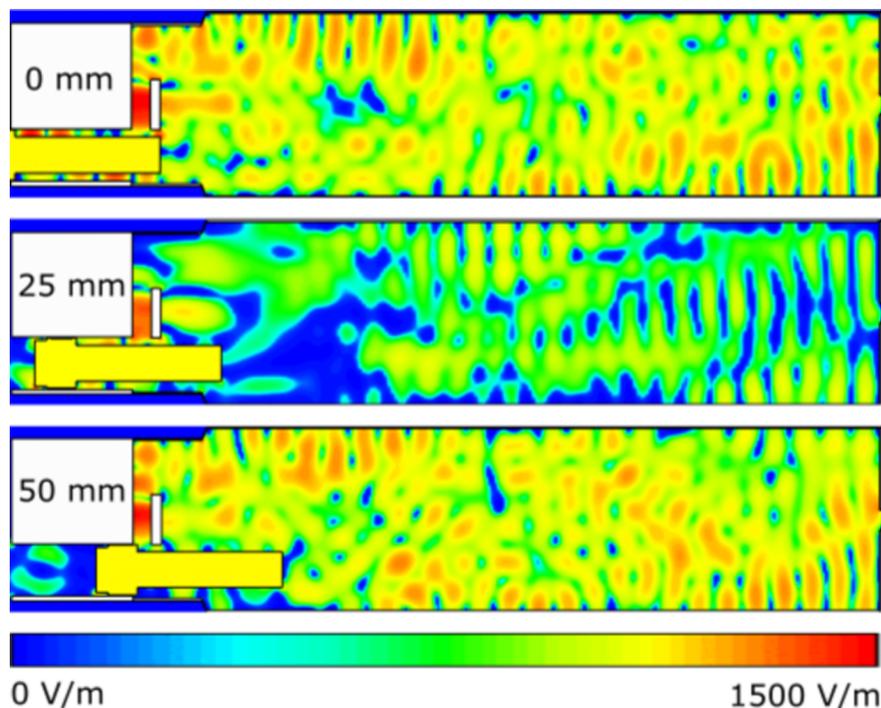


FIG. 2. Simulated rms electric field distribution in the plasma chamber of the JYFL 14 GHz ECRIS at tuner positions of 0, 25, and 50 mm and a frequency of 14.053 GHz. The tuner is shown at the bottom of each subfigure with yellow color and the injection plug and biased disc with white color.

S11-parameter were monitored hereafter. 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 11.56 GHz) provided by the TWT amplifier connected to the WR75 waveguide port. In this experiment, the network analyzer connected to the klystron waveguide (WR62 port) was protected from transmitted power with a high-pass filter. The power applied for sustaining the plasma was varied and the effect of the tuner position on the S11-parameter within the klystron bandwidth was studied at different microwave powers presumably corresponding to different plasma densities. Measurement of the S11-parameter allowed distinguishing certain frequencies of interest in the range of 14.00–14.15 GHz, 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 a single frequency heating mode with the klystron. The beam currents were measured from a Faraday cup located downstream from a $90^\circ m/q$ -analyzing magnet. The source potential was set to 10 kV, which is a typical value for the operation of the JYFL 14 GHz ECRIS. At 10 kV source potential, the transport efficiency of the low energy beamline is typically $\geq 70\%$. The transport efficiency is estimated by comparing the beam currents measured from the Faraday cup and the drain current of the high voltage power supply. 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 ≤ 7.5 kV potentially skewing the results. The extracted beams were focused into the Faraday cup with an einzel lens, solenoid, and xy-steering magnet located between the ion source and the bending magnet. In addition to the charge state distributions at the Faraday cup, the biased disc and total extracted currents were measured at each experimental setting.

Since the parameter space of ECRIS optimization is extensive, the microwave power, oxygen feed rate, and biased disc voltage were kept constant when moving the tuner. The experiment at each microwave frequency was started by setting the strength of the solenoid magnetic field to $B_{inj}/B_{ext}/B_{min} = 2.05/0.95/0.36$ T with the tuner fully retracted (at 0 mm). The field strength was chosen so that the B_{min}/B_{ECR} -ratio of 0.72 is below the threshold of kinetic plasma instabilities, typically appearing at a B_{min}/B_{ECR} -ratio of 0.75 at the (maximum) microwave power and gas pressure used in this study.²⁶ However, at certain tuner position / microwave frequency combinations the plasma exhibited “mode-hopping” as described further in Secs. III and IV. It was sometimes possible to suppress such behavior by a minor adjustment (less than 1%) of the magnetic field strength while at certain tuner position / microwave frequency combinations the “mode-hopping” persisted practically throughout the whole range of magnetic field values below the threshold of kinetic instabilities. Therefore, the extracted current of O^{6+} ion beam was optimized at each tuner position by adjusting the (solenoid) magnetic field strength by less than $\pm 1\%$ from the nominal

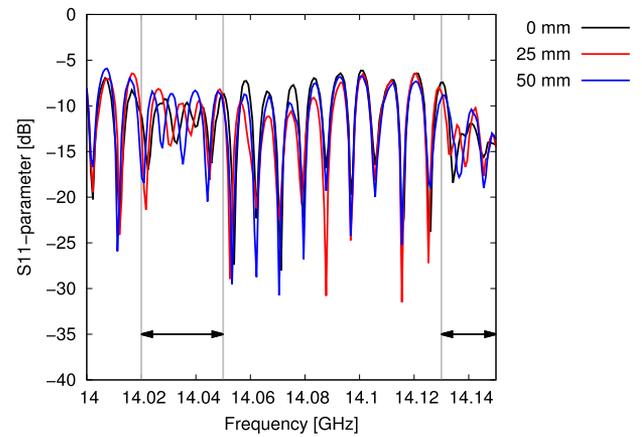


FIG. 3. The empty cavity S11-parameter of the complete klystron waveguide system as a function of the microwave frequency for some tuner positions. The vertical lines and horizontal arrows indicate the limits of the frequency ranges where the cavity effect superimposed on the periodic waveguide modes can be observed.

value shown above. The corresponding effect on the mirror ratio would be equal to moving the biased disc inwards by approximately 2 mm.

III. EXPERIMENTAL RESULTS

A. The effect of cavity tuning on the S11-parameter

Figure 3 shows the S11-parameter as a function of the microwave frequency measured through the complete klystron waveguide system (including the plasma chamber) with some tuner positions chosen as representative examples of the collected data. The range of the microwave frequency corresponds to the klystron bandwidth. The periodic ripple that is virtually immune to the tuner position and dominates the frequency response of the S11-parameter is due to the excitation of waveguide modes.¹⁸ The effect of the tuner can be best observed in narrow frequency ranges of 14.02–14.05 and 14.13–14.15 GHz where some seemingly random variations of the S11-parameter are seen superimposed on the periodic ripple caused by the waveguide modes. This was observed to be the case at all studied tuner positions, i.e., 5 mm steps from 0 to 50 mm.

Figure 4 shows the S11-parameter as a function of the microwave frequency with the network analyzer connected to the klystron waveguide close to the plasma chamber at the same tuner positions as previously. It can be seen that the strong periodic structure is not present anymore, which supports the interpretation that the ripple in Fig. 3 is caused by the waveguide modes. Certain frequencies at which the tuner position was observed to affect the cavity behavior throughout the entire adjustment range of the tuner have been identified in the figure (majority of the data are not presented in the figure). The frequencies indicated in the figure were used later when measuring the effect of the cavity tuning on the extracted beam currents.

The implication of Figs. 3 and 4 is that studying the excitation of cavity modes and the subsequent effect on the electron heating by varying the frequency is virtually impossible with the JYFL 14 GHz ECRIS due to the dominance of

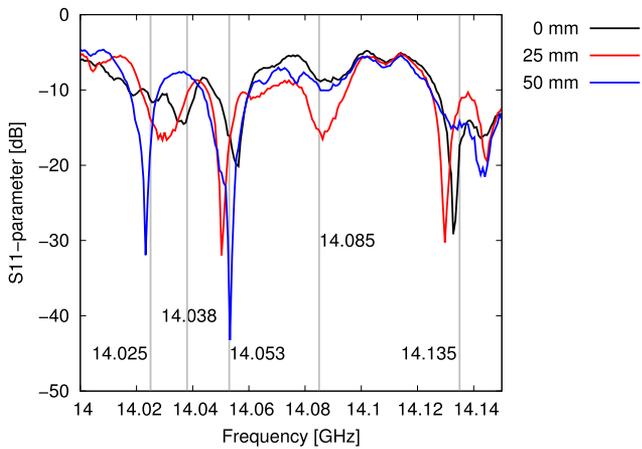


FIG. 4. The empty cavity S11-parameter as a function of the microwave frequency measured from the klystron waveguide close to the plasma chamber for several tuner positions. The vertical lines indicate some frequencies at which the tuner position affects the cavity behavior.

the waveguide system. On the other hand, the response of the source performance on the cavity properties can presumably be studied by using a fixed frequency and adjusting the tuner position. However, the presence of the plasma affects the cavity behavior significantly as demonstrated in Fig. 5 showing the S11-parameter at certain tuner positions in the frequency range of 14.00–14.15 GHz with the plasma sustained by 120 W TWTA power at 11.56 GHz. It was observed that 2 W of power from the TWTA 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, 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 effectively suppressed.

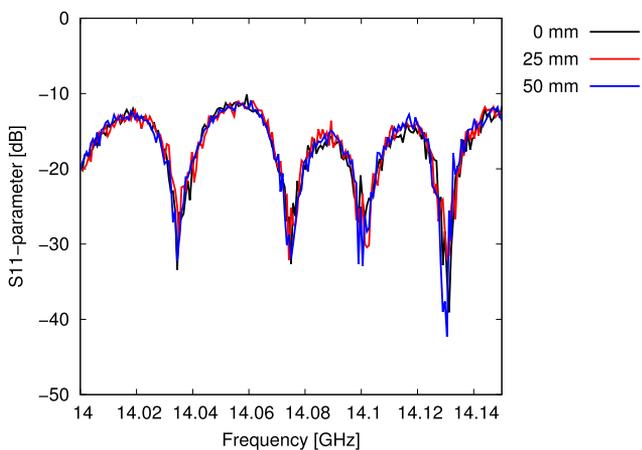


FIG. 5. The S11-parameter in the presence of the plasma sustained by 120 W power at 11.56 GHz as a function of the microwave frequency measured from the klystron waveguide close to the plasma chamber with some tuner positions.

B. The effect of cavity tuning on the extracted beam currents

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

Figures 6 and 7 show the recorded m/q-spectra at frequencies of 14.053 and 14.135 GHz, respectively. In both cases, the microwave power was kept constant at 400 W while all the other source parameters (magnetic field, gas pressure, and bias disc voltage) and extraction optics were first optimized for the charge state O^{6+} with the tuner at 0 mm. Only the magnetic field strength was then changed between different tuner positions to maximize the O^{6+} current. The data in Figs. 6 and 7 were chosen for display because they represent the frequencies being least (14.053 GHz) and most (14.135 GHz) sensitive to the tuner position. Three different m/q-spectra are shown in both figures—without the tuner (0 mm) and at tuner positions corresponding to maximum and minimum O^{6+} current obtained at the given frequency.

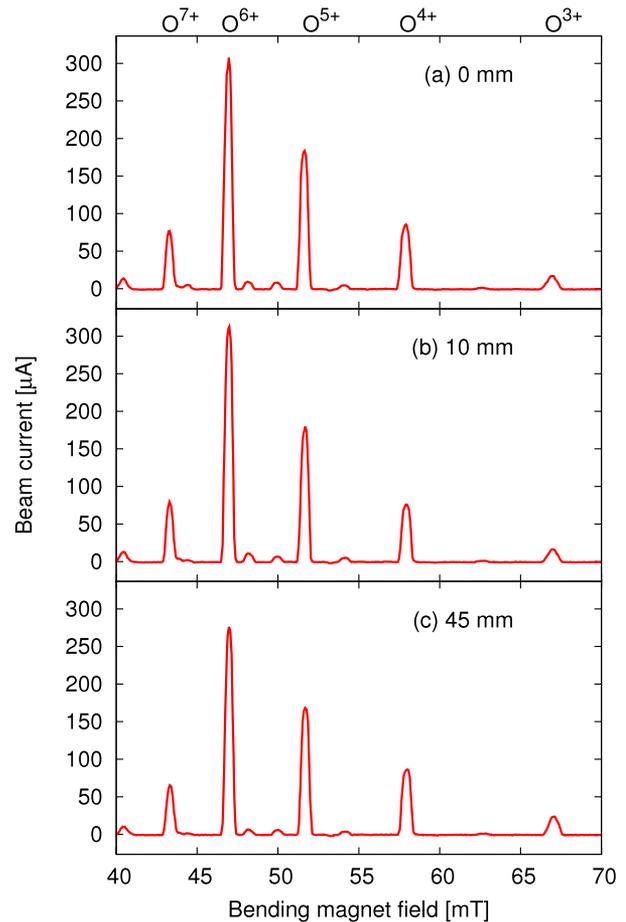


FIG. 6. The m/q-spectrum of oxygen recorded with 400 W at 14.053 GHz at the tuner positions of (a) 0 mm with 307 μA of O^{6+} , (b) 10 mm with 313 μA of O^{6+} (maximum), and (c) 45 mm with 276 μA of O^{6+} (minimum). The corresponding drain currents of the high voltage power supply are 1.21 mA, 1.16 mA, and 1.19 mA, respectively.

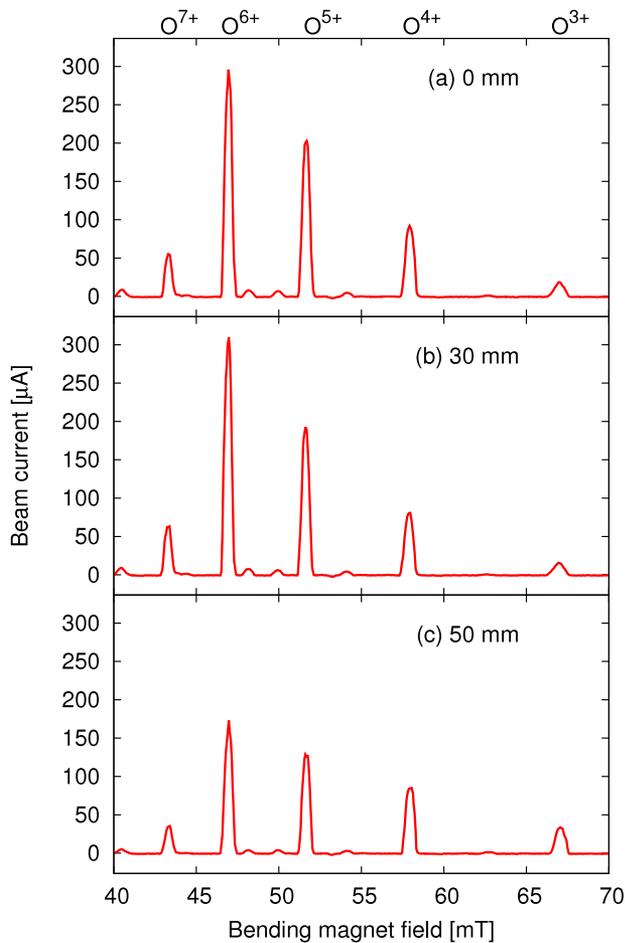


FIG. 7. The m/q -spectrum of oxygen recorded with 400 W at 14.135 GHz at the tuner positions of (a) 0 mm with 296 μA of O^{6+} , (b) 30 mm with 310 μA of O^{6+} (maximum), and (c) 50 mm with 172 μA of O^{6+} (minimum). The corresponding drain currents of the high voltage power supply are 1.27 mA, 1.25 mA, and 0.92 mA, respectively.

The (temporally averaged) O^{6+} currents obtained at each frequency and tuner position are displayed in Fig. 8. The data points at 5 mm interval correspond to the tuner positions at which the magnetic field was adjusted to maximize the current. No significant deviations from the trend shown in the figure were observed when adjusting the tuner position by 5 mm and monitoring the O^{6+} current on-line at fixed magnetic field. Data points where the so-called “mode-hopping” (see the following discussion) was observed are indicated in the figure. The lines connecting the data points have been added to guide the eye.

The results obtained with frequencies in the range of 14.00–14.15 GHz are summarized in Table I showing the baseline (tuner at 0 mm) as well as minimum and maximum currents of each charge state as a function of the tuner position varied from 0 to 50 mm at each frequency. The corresponding variation from the baseline is also listed in the table.

The results and observations can be summarized as follows:

1. Under stable plasma conditions the source performance (O^{6+} current is used as an indicator) is more sensitive to the tuner position than to the microwave frequency. For example, with the tuner at 0 mm the O^{6+} current varied from 279 to 307 μA , i.e., less than 5% of the average, with

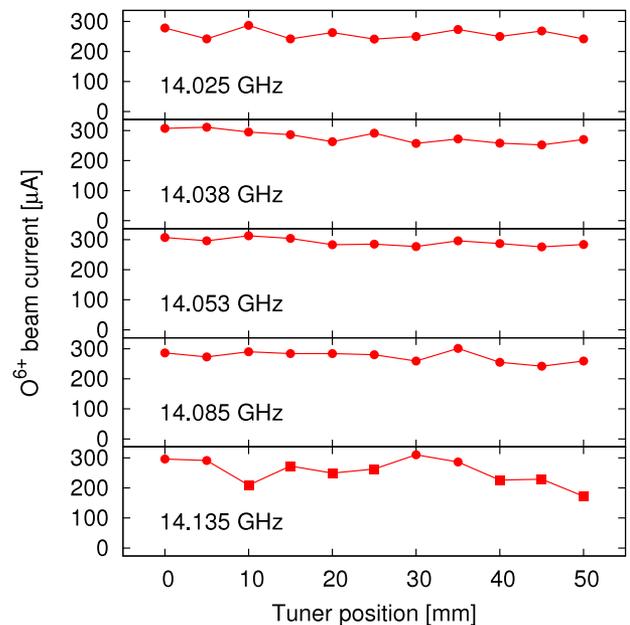


FIG. 8. Temporally averaged O^{6+} beam currents as a function of the tuner position at different microwave frequencies. The points of the data set at the bottom marked with ● and ■ correspond to stable and unstable (mode-hopping) plasma conditions, respectively.

the frequency (14.00–14.15 GHz) while the tuner position was observed to affect the current up to 20%.

2. The charge state distribution can be affected by the tuner position as seen especially in Fig. 7.
3. The optimum tuner position depends on the microwave frequency.
4. The extracted currents of the high charge state ions can be increased only moderately (<10% 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 14.00–14.15 GHz.
5. The S11-parameter cannot 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.
6. Varying the tuner position makes the plasma prone to being unstable, which explains the shift of the charge state distribution in some cases. The instability is not periodic and does not cause bursts of energetic electrons to escape from the confinement as often observed at strong magnetic fields²⁷ but rather manifests itself as 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 14.053 GHz there were no signs of the phenomenon while at 14.135 GHz mode transitions were observed with the majority of tuner positions, which explains the large (up to 40%) variation of the high charge state currents in the latter case. Susceptibility of the JYFL 14 GHz ECRIS to instabilities caused by mode-transitions at certain microwave frequency intervals

TABLE I. Baseline (tuner at 0 mm) and maximum/minimum currents of charge states O^{3+} – O^{7+} observed at different frequencies within the 50 mm adjustment range of the tuner.

Charge state	O^{3+}	O^{4+}	O^{5+}	O^{6+}	O^{7+}
$f = 14.025$ GHz					
$I_{baseline}$ (μA)	17	83	189	279	56
I_{max} (μA)	23	87	197	287	60
I_{min} (μA)	15	82	160	242	43
Variation (%)	+35/–12	+5/–1	+4/–15	+3/–13	+7/–23
$f = 14.038$ GHz					
$I_{baseline}$ (μA)	18	83	183	307	75
I_{max} (μA)	23	85	194	311	76
I_{min} (μA)	14	77	158	252	57
Variation (%)	+28/–22	+2/–7	+6/–14	+1/–18	+1/–24
$f = 14.053$ GHz					
$I_{baseline}$ (μA)	16	76	179	307	78
I_{max} (μA)	23	86	184	313	79
I_{min} (μA)	16	76	162	276	68
Variation (%)	+30/–0	+13/–0	+3/–9	+2/–10	+1/–13
$f = 14.085$ GHz					
$I_{baseline}$ (μA)	23	85	174	286	68
I_{max} (μA)	32	91	179	301	81
I_{min} (μA)	18	79	152	242	61
Variation (%)	+39/–22	+7/–7	+3/–13	+5/–15	+19/–10
$f = 14.135$ GHz					
$I_{baseline}$ (μA)	18	92	203	296	55
I_{max} (μA)	34	97	203	310	66
I_{min} (μA)	14	79	129	172	35
Variation (%)	+89/–22	+5/–14	+0/–36	+5/–42	+20/–36

explains the frequency dependent behavior of high charge state beam currents reported earlier in Ref. 17 (Figs. 1 and 3 therein). It must be noted that the comparison of different tuner positions under “mode-hopping” is somewhat ill-defined. Nevertheless, the frequencies (14.12–14.14 GHz) at which “mode-hopping” occurs should be avoided in regular operation.

IV. DISCUSSION

From the practical point-of-view, it is relevant to question whether cavity tuning is worth the complexity that its mechanical implementation requires. Based on the mere <5% increase in the intensity of the charge state for which the ion source was tuned, this does not seem to be the case. The tuner position was undoubtedly observed to affect the extracted currents and charge state distribution but in most cases adjusting the tuner position caused “mode-hopping,” which reduced the average currents of high charge state ions and made it difficult to tune the ion source.

It is, nevertheless, concluded that cavity tuning affects the plasma properties of the ECRIS. This is most likely due to the modified electric field structure. However, 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 in unstable operation due to the strong feedback loop. As already described, such mode-hopping effect was observed for certain frequency / tuner position combinations.

It can be expected that in the case of high-frequency, large plasma volume ECR ion sources the cavity tuning technique would be even less effective. This is because at short wavelengths the plasma chamber acts as an overmoded cavity in which the eigenmodes overlap due to plasma induced broadening. On the contrary, the geometry of the microwave launching system can be optimized in that case considering the first pass absorption of the microwave power at the resonance surface as demonstrated recently.²⁸

Finally, it is emphasized that the results are specific to the JYFL 14 GHz ECRIS operating in the frequency range of 14.00–14.15 GHz but together with the results reported in Refs. 14, 17, and 18 they indicate that the performance of A-ECR-type ion sources is less sensitive to frequency variations than the performance of Caprice-type ion sources. It is likely that the difference cannot be attributed to cavity modes but could be explained by different microwave-plasma coupling schemes.

In summary, it is concluded that neither frequency tuning nor cavity tuning can be applied to significantly improve the performance of the A-ECR type JYFL 14 GHz ECRIS operating in single frequency heating mode.

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