Studying the double-frequency heating mode in ECRIS plasma using Kα diagnostics

Muneer Sakildien, Olli Tarvainen, Risto Kronholm, Taneli Kalvas, Pete Jones, and Hannu Koivisto

Citation: AIP Conference Proceedings **2011**, 040011 (2018); doi: 10.1063/1.5053285
View online: https://doi.org/10.1063/1.5053285
View Table of Contents: http://aip.scitation.org/toc/apc/2011/1
Published by the American Institute of Physics

Studying the double-frequency heating mode in ECRIS plasma using Kα diagnostics

Muneer Sakildien[1,3,a)], Olli Tarvainen[3], Risto Kronholm[3], Taneli Kalvas[3], Pete Jones[2] and Hannu Koivisto[3]

[1]*Accelerator and Engineering Department, iThemba LABS, P.O. Box 722, Somerset West, 7131, South Africa.*
[2]*Subatomic Physics Department, iThemba LABS, P.O. Box 722, Somerset West, 7131, South Africa.*
[3]*Department of Physics, University of Jyväskylä, Jyväskylä 40500, Finland.*

[a)]Corresponding author: muneer@tlabs.ac.za

Abstract. Despite the success of double-heating frequency in enhancing high charge state production, the underlying physics remains poorly understood. By combining three different diagnostic techniques i.e. Kα emission, optical emission and the extracted charge state distribution, it is now possible to assess the proposed explanations for the effectiveness of double-frequency heating against the experimental results. These results seem to indicate that the increase of plasma density accounts largely for the favorable behavior of this operation mode compared to single-frequency mode.

INTRODUCTION

Heating the plasma of an Electron Cyclotron Resonance Ion Source (ECRIS) with multiple frequencies, as opposed to a single frequency, enhances the extracted ion beam current of high charge states [1]. Despite numerous investigations into multiple frequency heating, the exact reason for its favorable influence remains poorly understood. Some plausible explanations for its effectiveness include increasing the plasma density, improving plasma stability and modifying the plasma potential structure [2]. All these proposed explanations appear to be linked to a modification of the electron density and energy distribution resulting to an increase in the ionization rate and ion confinement time.

To gain understanding on the impact of double-frequency heating on high charge state production, the axially emitted characteristic Kα emission from the argon plasma of an ECRIS was measured, in conjunction with radial optical light emission ($2s^22p^2\ P^\circ_{3/2} \longrightarrow 2s^22p^2\ P^\circ_{1/2}$ for Ar^{13+} and $2s^22p^5\ P^\circ_{1/2} \longrightarrow 2s^22p^5\ P^\circ_{3/2}$ for Ar^{9+}) from ions, as well as their beam currents. The measured Kα emission rate is proportional to the electron density, argon density (neutrals and ions) and the rate coefficient for inner shell ionization. The Kα emission allows us to assess the relative influence of the electron density and rate coefficient on high charge state production, thus enabling us to gauge the different mechanisms proposed to explain the favorable effect of double-frequency heating against the Kα diagnostics supported by the optical emission data and beam currents. Furthermore, the Kα emission rate of argon was compared to the Kα emission rate of iron originating from the stainless steel biased disc, which enables probing the effect of double-frequency heating on electron confinement and losses.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup used for this work has been extensively described previously [3] and only the main features will be mentioned here. To measure the Kα emission, the JYFL 14 GHz ECRIS [4] was utilized. This ECRIS, which is equipped with a klystron and a traveling wave tube amplifier (TWTA), was operated in double-frequency heating mode with the TWTA frequency varied between 11.100 GHz and 12.450 GHz and the klystron frequency fixed at 14.056 GHz. The x-ray detector used to measure the Kα emission was positioned to view the plasma volume and biased disc surface through a port on the vacuum chamber of the 90 degree bending magnet 2.6 m downstream in

Proceedings of the 17th International Conference on Ion Sources
AIP Conf. Proc. 2011, 040011-1–040011-3; https://doi.org/10.1063/1.5053285
Published by AIP Publishing. 978-0-7354-1727-4/$30.00

the beamline. A ϕ = 0.90 mm collimator was installed in front of the detector to limit the solid angle, thus observing emission (mostly) from the plasma volume and thick target radiation from the biased disc.

The source was first operated in single-frequency mode. The Kα emission rate was measured at three microwave powers, with the frequency delivered from the TWTA varied at each of them. This allowed for probing the effect of the plasma heating frequency on the diagnostics signals. The axial magnetic field profile was scaled to maintain a constant injection mirror ratio $R_{\mathrm{inj}} = B_{\mathrm{inj}}/B_{\mathrm{ecr}} = 3.87$ at the different heating frequencies. Finally, the source was operated in double-frequency mode varying the power ratio of the klystron and the TWTA at constant total power. The source was optimized separately for Ar^{9+} and Ar^{13+} and the emission rates of the Kα and optical transitions of the afore-mentioned ions were recorded.

RESULTS AND DISCUSSION

An example of the results, namely the Ar and Fe Kα emission rates and their ratios (r), obtained in single frequency operation mode with 150 W power (< 2 W reflected) and constant injection mirror ratio is presented in Table 1. The table also lists the volumetric emission rate of Ar Kα, averaged over the plasma volume visible to the x-ray detector, and the corresponding beam current of Ar^{9+}. It is evident that both, the inner shell ionization rate of argon (indicated by the Kα count rate) and extracted beam current of Ar^{9+} (first charge state with empty M-shell) increase with the microwave frequency. The frequency trend of the inner shell ionization rate can most likely be explained by the electron density increasing with the frequency, which also favors the high charge state ion beam production. Simultaneously it was observed that the Fe-to-Ar Kα ratio (r) displays the opposite frequency trend. Here r can be used as an indication of the warm electron losses towards the biased disc (at the energies close to Kα). The result leads us to conclude that the electron losses of the afore-mentioned population toward the bias disk are not determined exclusively by the mirror ratio R_{inj}, which is often used to describe the magnetic field of ECRISs [5].

TABLE 1: Ar and Fe Kα counts, Fe-to-Ar Kα ratio (r) and extracted Ar^{9+} beam current as a function of the microwave frequency at constant 150 W power and $R_{\mathrm{inj}} = 3.87$. The volumetric rate is calculated for the plasma volume visible to the x-ray detector.

Frequency [GHz]	**Ar Kα counts [cps]**	**Fe Kα counts [cps]**	**Fe-to-Ar Kα-ratio (r)**	**Ar Kα volumetric rate [counts/ cm^3]**	**Ar^{9+} current [μA]**
11.100	110	720	6.4	9.9×10^{9}	17
11.560	200	1010	5.1	1.7×10^{10}	35
12.450	290	860	2.9	2.6×10^{10}	50
14.056	600	160	0.3	5.2×10^{10}	81

When comparing the single and double-frequency operation modes at constant total powers, i.e. 520 W (Ar^{13+} tune) or 320 W (Ar^{9+} tune) delivered from the klystron (14.05 GHz) and another 10 – 100 W from either the klystron or the TWTA (11.56 GHz), it was observed that the additional frequency only becomes effective if the source is tuned for high charge state production i.e. Ar^{13+} as opposed to Ar^{9+}. This is evident from the Kα emission, as well as the light emission signals of the given charge states and their extracted beam currents shown in Fig. 1. Furthermore, it is observed that the Fe-to-Ar Kα ratio decreases with added power in double-frequency mode with the source tuned for Ar^{13+} indicating that the relative electron losses towards the biased disc decrease in that case. With the source tuned for Ar^{9+} these trends revealing a clear difference between the single and double frequency heating modes are not visible as shown in Fig. 2. This strengthens the argument that the secondary frequency only becomes effective with the source tuned for high charge state production as discussed e.g. in Ref. [2].

Assessing the proposed explanations put forward for the effectiveness of double-heating frequency, the measured results seems to suggest that the increase in plasma density in comparison to single frequency operation accounts for the effect. Judging by the trends of the Fe-to-Ar Kα emission ratios (see Fig. 1), it seems clear that, in relative terms, less electrons are expelled from the magnetic confinement system if the source is operated in double-frequency mode. This appears to indicate that the division of the power between two frequencies, i.e. power deposition on two concentric resonance zones instead of one, affects the RF pitch angle scattering rate [6] and/or improves the stability of the plasma [7]. However, the detector used for this investigation is not able to measure quick bursts of bremsstrahlung,

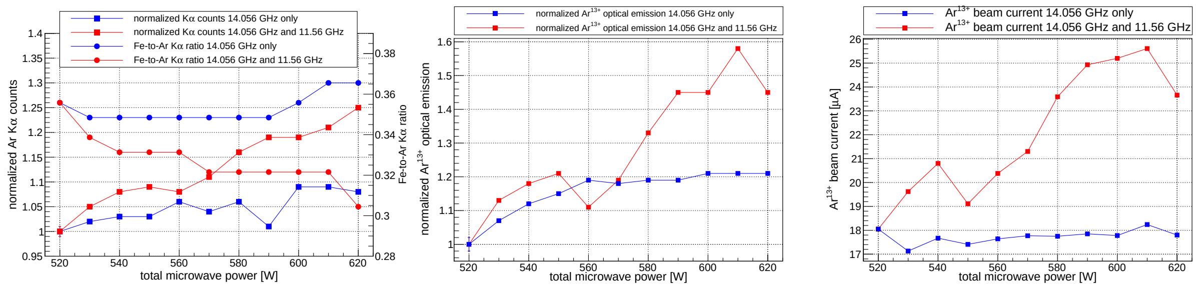

FIGURE 1: Normalized Ar Kα counts and the Fe-to-Ar Kα ratio (left), normalized optical emission for $2s^22p^2\ P^{\circ}_{3/2} \longrightarrow 2s^22p^2\ P^{\circ}_{1/2}$ transition of Ar^{13+} (middle) and the Ar^{13+} beam current (right), with the source optimized for Ar^{13+}.

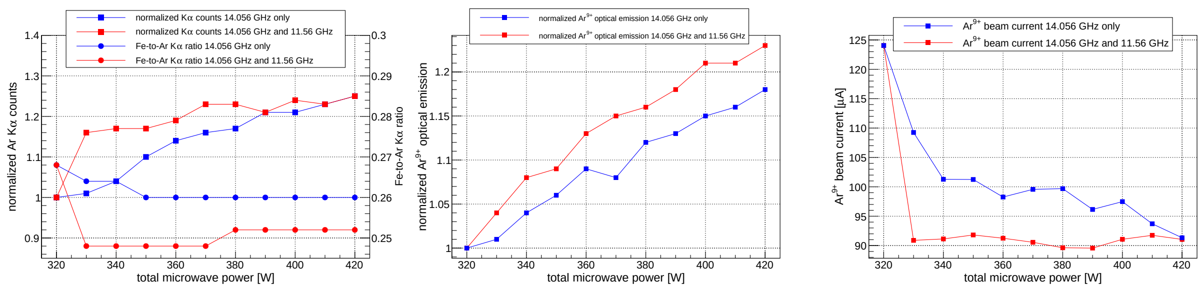

FIGURE 2: Normalized Ar Kα counts and the Fe-to-Ar Kα ratio (left), normalized optical emission for $2s^22p^5\ P^{\circ}_{1/2} \longrightarrow 2s^22p^5\ P^{\circ}_{3/2}$ transition of Ar^{9+} (middle) and the Ar^{9+} beam current (right), with the source optimized for Ar^{9+}.

as expected when the plasma experiences kinetic instabilities [8]. We can therefore not make any definitive statements concerning the stability of the plasma.

ACKNOWLEDGMENTS

This work was supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2012-2017 (Project No. 213503, Nuclear and Accelerator-Based Physics Research at JYFL). The work is also based on the research supported in part by iThemba LABS and the National Research Foundation of South Africa (Grant Reference No.: 109887 and 110072). The first author would also like to acknowledge the Department of Physics at the University of Stellenbosch for the loan of their x-ray detector.

REFERENCES

[1] Z. Q. Xie and C. M. Lyneis *Proc. 12th Intl. Workshop on ECR Ion Sources*, Riken, Japan, (1995).
[2] R.C. Vondrasek, R. Scott and R.C. Pardo *Rev. Sci. Instrum.* ***77**, 03A337*, (2006).
[3] M. Sakildien, R Kronholm, O Tarvainen, T Kalvas, P Jones, R Thomae and H Koivisto, "Inner shell ionization of argon in ECRIS plasma", submitted to Nucl. Instrum. Meth. Phys. Res. A, (2017).
[4] H. Koivisto, P. Heikkinen, V. Hänninen, A. Lassila, H. Leinonen, V. Nieminen, J. Pakarinen, K. Ranttila, J. Ärje and E. Liukkonen, *Nucl. Instrum. Meth. Phys. Res. B* ***174** (3)*, (2001) 379-384.
[5] R. Geller, *Annu. Rev. Nucl. Part. Sci.* ***40***, (1990) 1543.
[6] B.P. Cluggish, L. Zhao and J.-S. Kim, *Nucl. Instrum. Meth. Phys. Res. A* ***631***, (2011).
[7] V. Skalyga, I. Izotov, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen, D. Mansfeld and O. Tarvainen, *Phys. Plasmas* ***22**, 083509*, (2015).
[8] O. Tarvainen, I. Izotov, D. Mansfeld, V. Skalyga, S. Golubev, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen and V. Toivanen, *Plasma Sources Sci. Technol. 23, 025020*, (2014).