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Studying the double-frequency heating mode in ECRIS plasma using $K\alpha$ diagnostics

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Studying the double-frequency heating mode in ECRIS plasma using $K\alpha$ diagnostics

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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. $K\alpha$ 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 $K\alpha$ emission from the argon plasma of an ECRIS was measured, in conjunction with radial optical light emission ($2s^22p^2 P_{3/2}^o \rightarrow 2s^22p^2 P_{1/2}^o$ for Ar^{13+} and $2s^22p^5 P_{1/2}^o \rightarrow 2s^22p^5 P_{3/2}^o$ for Ar^{9+}) from ions, as well as their beam currents. The measured $K\alpha$ emission rate is proportional to the electron density, argon density (neutrals and ions) and the rate coefficient for inner shell ionization. The $K\alpha$ 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 $K\alpha$ diagnostics supported by the optical emission data and beam currents. Furthermore, the $K\alpha$ emission rate of argon was compared to the $K\alpha$ 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 $K\alpha$ 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 $K\alpha$ 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

the beamline. A $\phi = 0.90$ 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 $K\alpha$ 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 $R_{inj} = B_{inj}/B_{ecr} = 3.87$ 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 $K\alpha$ and optical transitions of the afore-mentioned ions were recorded.

RESULTS AND DISCUSSION

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

Frequency [GHz]	Ar $K\alpha$ counts [cps]	Fe $K\alpha$ counts [cps]	Fe-to-Ar $K\alpha$ -ratio (r)	Ar $K\alpha$ volumetric rate [counts/ cm ³]	Ar^{9+} current [μ A]
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 $K\alpha$ 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 $K\alpha$ 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 $K\alpha$ 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,

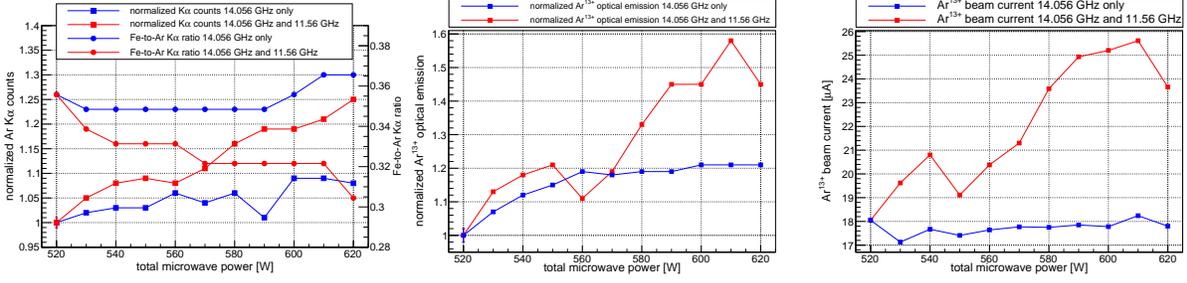


FIGURE 1: Normalized Ar $K\alpha$ counts and the Fe-to-Ar $K\alpha$ ratio (left), normalized optical emission for $2s^22p^2 P^{\circ}_{3/2} \rightarrow 2s^22p^2 P^{\circ}_{1/2}$ transition of Ar^{13+} (middle) and the Ar^{13+} beam current (right), with the source optimized for Ar^{13+} .

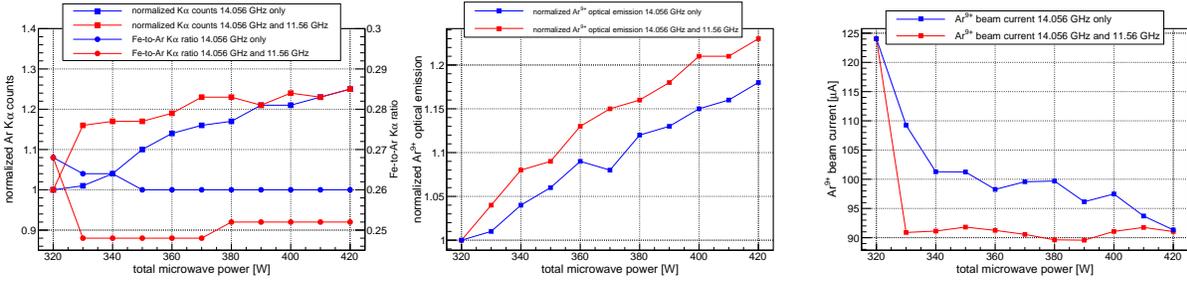


FIGURE 2: Normalized Ar $K\alpha$ counts and the Fe-to-Ar $K\alpha$ ratio (left), normalized optical emission for $2s^22p^5 P^{\circ}_{3/2} \rightarrow 2s^22p^5 P^{\circ}_{1/2}$ transition of Ar^{9+} (middle) and the Ar^{9+} beam current (right), with the source optimized for Ar^{9+} .

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

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