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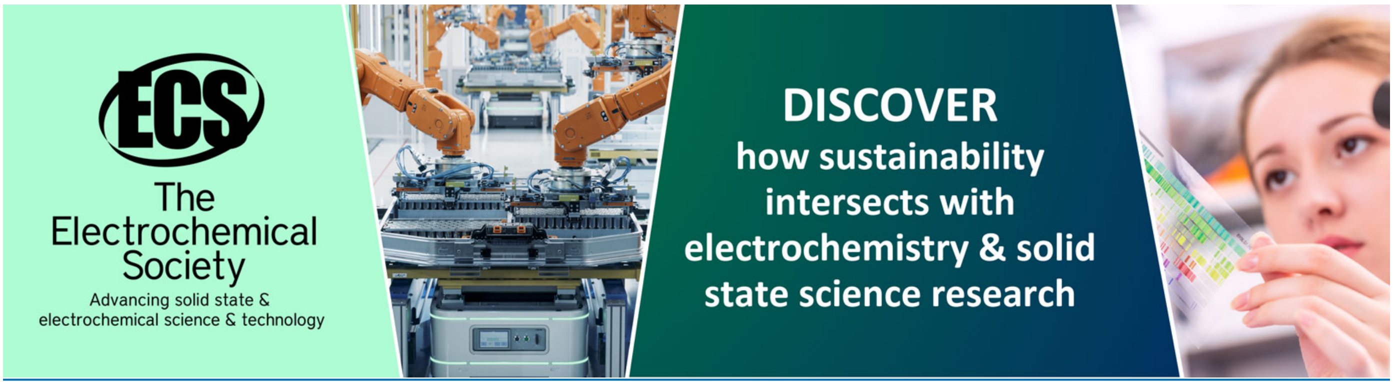

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# Gas mixing and double frequency operation of the permanent magnet quadrupole minimum-B electron cyclotron resonance ion source CUBE-ECRIS

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**Abstract.** CUBE-ECRIS is a recently commissioned permanent magnet electron cyclotron resonance (ECR) ion source developed at the university of Jyväskylä accelerator laboratory. The special features of the new ion source design include an unconventional quadrupole minimum-B magnetic field structure and a slit beam extraction system necessitated by the line-shaped plasma loss fluxes. Gas mixing and double frequency operation are widely used methods to optimize high charge state ion production of conventional ECR ion sources. The work presented here demonstrates the applicability of these methods for boosting the high charge state beam currents of argon, krypton and xenon extracted from CUBE-ECRIS. Oxygen and helium were used as mixing gases and microwave frequencies between 10 and 11 GHz were used for single and double frequency operation. Gas mixing has a strong impact on the high charge state beam currents. For example, the highest observed charge state increased from 15+ to 19+ for krypton and from 16+ to 23+ for xenon with oxygen gas mixing. Double frequency operation provides an additional performance improvement, for example the currents of argon 9+ and 11+ beams, produced with gas mixing, increased 30% and 100% in double frequency operation at the same total power.

## 1. Introduction

CUBE-ECRIS is a 10 GHz permanent magnet electron cyclotron resonance (ECR) ion source based on the ARC-ECRIS quadrupole minimum-B field structure [1]. This confinement scheme is a potential alternative for the conventional ECRIS minimum-B configuration which is realized as a superposition of sextupole and solenoid fields, created with a nested magnetic structure. One of the advantages of the ARC-ECRIS field structure, which can be created with 'baseball-seam' shaped coils, is that it has been shown to be theoretically scalable up to 100 GHz operation using existing superconducting technology [2] – something that currently seems to be unfeasible with the conventional ECRIS magnetic configuration. CUBE-ECRIS represents an intermediate step to develope the ARC-ECRIS concept towards higher frequency operation, and it has been built to further study the use of this unconventional B field structure for plasma confinement, production of highly charged ions and beam formation with a slit beam extraction system; a

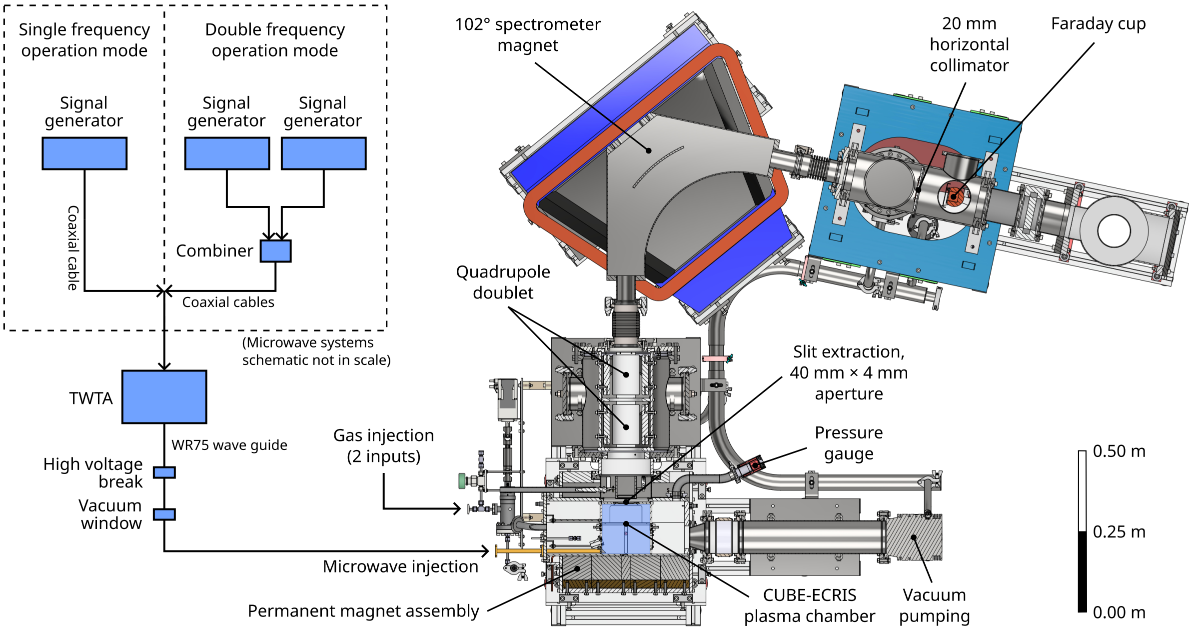

**Figure 1.** A cross section view of the CUBE-ECRIS ion source and the low energy beam transport with a schematic of the microwave systems for single and double frequency operation.

feature that is necessitated by the line-shaped plasma loss fluxes. The design and the first experimental results of CUBE-ECRIS have been reported in detail in Refs. [3, 4, 5].

Gas mixing and multiple frequency operation have become standard techniques with conventional ECR ion sources to optimize the high charge state ion production. As such, verifying the applicability of these methods with the unconventional quadrupole minimum-B plasma confinement scheme is a relevant part in the development of the ARC-ECRIS concept. In gas mixing method, first reported by Drentje [6] and Jacquot [7], a gas of lower atomic mass is mixed with the heavier main gas, i.e. the element of interest. As a result, a substantial improvement is achieved in the beam currents of the high charge states of the heavier gas species. Another method to improve the high charge state performance is multiple frequency operation, first demonstrated by Xie and Lyneis [8]. In this method, microwaves at two or more discrete frequencies are simultaneously injected into the plasma, which provides improved plasma heating, mitigation of plasma instabilities and improved ion confinement times [9, 10]. In the work presented here the applicability of these two methods was probed experimentally by studying their effectiveness in improving the high charge state performance of CUBE-ECRIS.

## 2. Experimental setup and procedure

The CUBE-ECRIS test stand is presented in Fig. 1. It consists of the CUBE-ECRIS ion source and a low energy beam transport (LEBT) section with a quadrupole doublet for beam focusing, a 102° spectrometer magnet for $m/q$ separation of the extracted ion beams and two vacuum chambers for beam diagnostics. A Faraday cup, located downstream from the spectrometer in the first diagnostics chamber, was the main beam diagnostic used in the presented work.

The microwave system of CUBE-ECRIS includes two Keysight EXG series variable frequency signal generators, a XICOM Technologies travelling wave tube amplifier (TWTA) with a maximum output power of about 300 W for 10–11 GHz frequencies and a WR75 rectangular wave guide transmission line connecting the TWTA to the CUBE-ECRIS plasma chamber via high voltage and vacuum breaks. The CUBE-ECRIS can be operated either in single or double frequency mode. In single frequency mode the output from one signal generator is amplified with the TWTA and then transmitted to the plasma chamber, whereas in double frequency mode the outputs from two signal generators are first combined at low power and then amplified with the TWTA. A schematic of the CUBE-ECRIS microwave system is presented in Fig. 1. Two precision valves are used for gas injection into the plasma chamber, allowing simultaneous operation with multiple gas species.

The effect of gas mixing on the high charge state beam currents was studied using argon, krypton and xenon plasmas. All the presented measurements were performed with 10 kV beam extraction and a 40 mm (horizontal) by 4 mm (vertical) rectangular slit extraction aperture. For each studied element, the ion source settings (puller and biased disc voltages, gas injection, microwave frequency and power) were first tuned to maximize the extracted beam current of the highest clearly observed charge state, and the resulting charge state distribution (CSD) was recorded. The system was subsequently retuned with mixing gas. Oxygen was chosen as the main mixing gas, as it is arguably the most commonly used element for this purpose with conventional ECR ion sources, and is typically reported to provide the best high charge state performance [11, 12, 13]. For comparison purposes, helium mixing was also tested with argon. The single versus double frequency operation study was performed with mixing gas in order to maximize the overall high charge state performance. In double frequency operation only the second frequency and the division of the total microwave power between the two frequencies were optimized, keeping the total forward microwave power and the other ion source settings constant to make the results comparable with the studies that have been performed in this manner with conventional ECR ion sources. In all the measured cases the highest high charge state ion performance was achieved using the maximum available microwave power of 300 W.

## 3. Results

The results of the gas mixing and double frequency operation are presented in Figs. 2 and 3, respectively. The presented data focuses on the high end of the CSDs, as the highest charge states benefit the most from the performance improvements provided by these methods. Improvement factors, presented at the bottom section of the figures, have been calculated for the measured argon, krypton and xenon charge states to characterise the effects on the measured ion beam currents. The improvement factor is defined as the ratio of the ion beam currents measured with and without gas mixing in Fig. 2, and as the ratio of the currents measured with double and single frequency operation in Fig. 3.

As is seen in Fig. 2, gas mixing provides a significant positive effect on the high charge state performance of argon, krypton and xenon. With krypton the highest observed charge state increased from 15+ to 19+ and with xenon from 16+ to 23+. For argon, 11+ was the highest clearly observable charge state because 12+ is obscured by an overlap with $^{16}\mathrm{O}^{5+}$ and $^{14}\mathrm{N}^{4+}$ beams. As such, no increase in the highest observed charge state could be clearly determined for argon. Considering the beam currents, with oxygen gas mixing for example the $^{40}\mathrm{Ar}^{9+}$ beam current improved by a factor of about 11, $^{84}\mathrm{Kr}^{14+}$ by a factor of about 9 and $^{131}\mathrm{Xe}^{15+}$ by a factor of about 14. Helium also improved the beam currents of the argon high charge states, but the effect was significantly weaker compared to oxygen; for example a factor of 1.2 was achieved for the $^{40}\mathrm{Ar}^{9+}$ beam current.

Double frequency operation provided an additional performance improvement on top of the gas mixing effect for the highest measured charge states, as is shown in Fig. 3. For example, $^{40}\mathrm{Ar}^{11+}$ beam current improved by a factor of about 2, and $^{84}\mathrm{Kr}^{19+}$ by a factor of about 1.3. With xenon, no improvement was observed with double frequency operation. It is suspected, that this could be due to CUBE-ECRIS not producing high enough xenon charge states that would benefit from the double frequency effect. This is commensurate with the improvement of

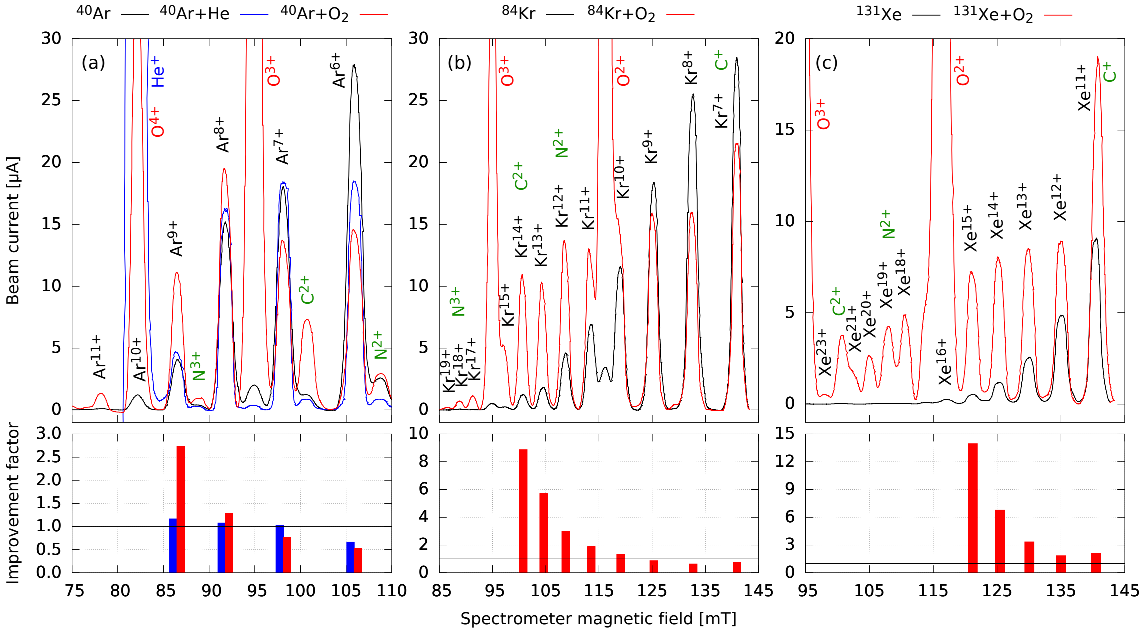

**Figure 2.** The top plots show the charge state distributions with and without gas mixing. He and $O_2$ were used as mixing gases with $^{40}$Ar (a). $O_2$ was used as mixing gas with $^{84}$Kr (b) and $^{131}$Xe (c). The bottom plots show the improvement factor gained with the gas mixing for different ion species. For argon the red bars corresponds to gas mixing with oxygen and the blue bars with helium.

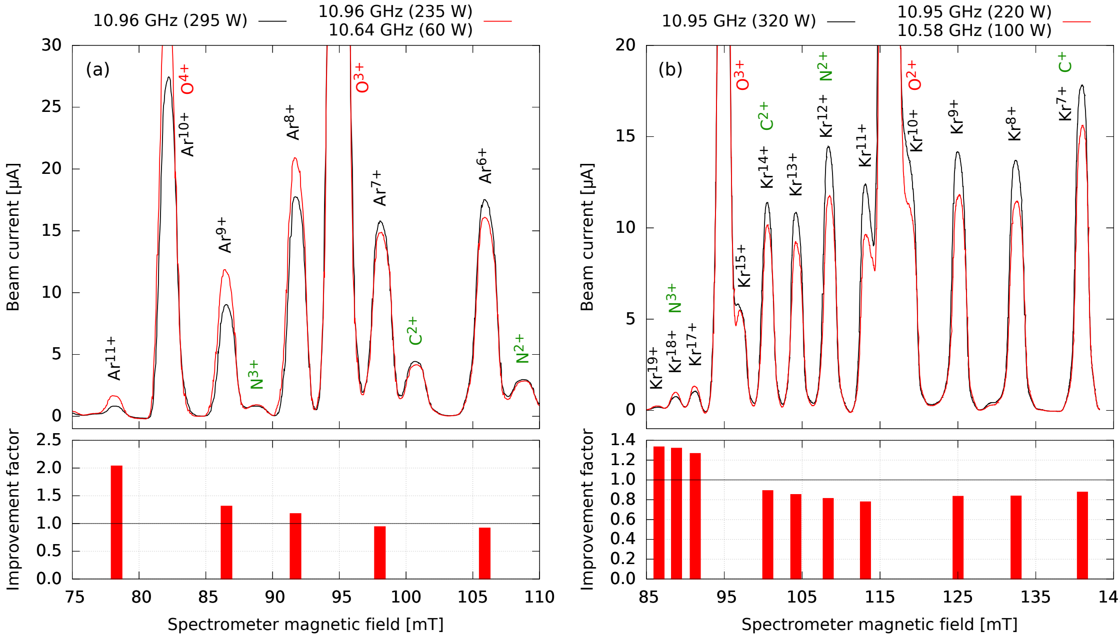

**Figure 3.** The top plots show the charge state distributions of $^{40}$Ar (a) and $^{84}$Kr (b) with single and double frequency operation. $O_2$ was used as mixing gas in all cases. The bottom plots show the improvement factor gained with double frequency operation for different ion species.

krypton high charge state currents with double frequency operation being weaker than those of argon.

## 4. Discussion and conclusions

The results show that gas mixing and double frequency operation provide high charge state performance improvement also with the unconventional quadrupole minimum-B plasma confinement scheme. The beam current improvements provided by gas mixing follow the same trends as has been seen with conventional ECRIS, namely that oxygen gives better performance compared to helium, the current improvement increases with increasing charge state, and the measured current improvement factors are comparable to those measured with conventional ECR ion sources (see e.g. [11, 12, 13]). With double frequency heating the CSD is also observed to shift towards higher charge states and the obtained performance improvements are in line with those reported for conventional ECRISs for high and medium charge states (see e.g. [8, 9, 14, 15]).

In all cases the best high charge state beam currents were achieved using the maximum available microwave power. This is a clear implication that CUBE-ECRIS performance is currently power limited. This behaviour has also been seen in previous experiments with CUBE-ECRIS [4, 5], and the planned future development of the CUBE-ECRIS test stand aims to increase the available microwave power.

In conclusion, the results presented here show that gas mixing and double frequency heating, which are widely used methods to optimize the ECR-heated plasma conditions for the production of high charge state ions in conventional ECR ion sources, work also with the unconventional quadrupole minimum-B magnetic structure. Consequently, this aspect will not be a hindrance in the further development of this concept towards more powerful future ion sources.

## Acknowledgments

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