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Investigation into the gas mixing effect in ECRIS plasma using Kα and optical diagnostics

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Abstract. Mixing a lighter gas species into the plasma of an ECRIS is known to enhance high charge state production of the heavier gas species. With this investigation, Kα diagnostics, optical emission spectroscopy and the measured charge state distribution of the extracted beam were combined to shed more light on the physics governing this phenomenon. Kα diagnostics data from two ion sources, the JYFL 14 GHz ECRIS and the GTS at iThemba LABS, are presented to gain confidence on the observed trends. The results seem to favor ion cooling as the most likely mechanism responsible for the favorable influence of the gas mixing.

INTRODUCTION

Adding a lighter mixing gas into the plasma of an Electron Cyclotron Resonance Ion Source (ECRIS) is known to enhance the highly charged ion (HCI) production of the heavier component, especially with of the mixture ratio [1]. Various explanations have been proposed for the beneficial effect. It has been suggested that the average charge state in the plasma is reduced, which increases the energy lifetime of the ions finally resulting to enhanced ion confinement and increased HCI production of the heavier minority species [2]. Another, perhaps the prevailing, explanation is attributed to ion cooling, resulting from the collisional interaction between the two gas species, with the lighter ions being heated and the heavier ones being cooled, thus increasing the confinement time of the latter [3]. Other explanations credit the increase in electron density and ionization efficiency of the heavier gas resulting in increased HCI production [4]. Yet another proposed explanation is the improvement of the plasma stability [5]. To develop the current understanding of the underlying physics of the gas mixing, Kα diagnostics, optical emission spectroscopy and the measured charge state distribution of the extracted beam were combined to study this phenomenon. The Kα emission rate Φ_R is proportional to the electron density, gas density (neutrals and ions) and the rate coefficient for inner shell ionization i.e. $\Phi_R \propto n_e n_{Ar} \langle \sigma_{ion} v_e \rangle$. The optical diagnostics were focused on probing the emission intensity of low charge states presumably playing a key role in gas mixing. Combining the results of the different diagnostics methods enables gauging different mechanisms listed above.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental data have been obtained on two different ECR ion sources i.e. the JYFL 14 GHz ECRIS[6] and the 14.5 GHz Grenoble Test Source (GTS)[7] at iThemba LABS. With both sources a silicon drift detector was mounted in one of the vacuum chamber ports of the bending magnet, to view the axially emitted Kα radiation. In order to minimize the contribution from wall bremsstrahlung, the emitted x-ray flux was collimated, by a ϕ =900 μm / ϕ =500 μm (JYFL / iThemba LABS), 20 mm long lead channel placed in front of the detector. The optical emission data was only measured on the JYFL 14 GHz ECRIS using a high throughput Fastie-Ebert monochromator coupled with a photomultiplier tube detector with a phase-sensitive lock-in detection setup, connected to the radial port of the ion source through an optical fiber. The beam currents were also recorded, simultaneously with the x-ray and the

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optical emission spectra. At JYFL the m/q range was limited to ≤ 8 with 10 kV extraction voltage and at iThemba LABS the transport efficiency of the extracted beams was limited. In both cases argon was used as working gas. In the measurements performed on the JYFL 14 GHz ECRIS, helium, neon and krypton were used as mixing gases. With the GTS, data were taken additionally with oxygen and xenon. To gain information on the behavior of the low charge state ions, the optical emission from the transition $3s^2 3p^4 (^3P) 4p\ ^4D^\circ_{5/2} \rightarrow 3s^2 3p^4 (^3P) 4s\ ^4P^\circ_{3/2}$ of Ar^{1+} was measured. This transition has an observed wavelength of 442.60008 nm. From results presented earlier, it has been shown that the optical emission of a particular charge state correlates very well with the extracted ion beam current of that charge state implying that the optical emission signal is directly proportional to the density of the given charge state in the core plasma.

In the experiments presented here the flow rate of the working gas (Ar) was kept constant while the flow rate of the mixing gas was varied without optimizing the mixture ratio for any particular charge state. As the response of the pressure gauge strongly depends on the gas composition, and the actual neutral gas pressure in the plasma chamber is unknown due to complex arrangement of the vacuum pumps, the results in the following section will be presented as a function of the valve setting of the mixing gas. This choice is further supported by the fact that both, the bias disc current and the source drain current, were not observed to follow the gas flow rate monotonically which invalidates them from being a measure of the neutral gas pressure. On the contrary, relating the total pressure measured by the ionization gauge of the 14 GHz JYFL ECRIS, to the valve setting, it was found that the behavior is well described by a quadratic function.

RESULTS AND DISCUSSION

Fig. 1 shows the normalized Ar Kα emission rates measured on the two ECR ion sources as a function of mixing gas valve setting (flow rate). The normalized Ar Kα emission rate was obtained by removing the continuum bremsstrahlung background spectrum from the raw measured spectrum, fitting a Gaussian distribution over the Ar Kα line, integrating over the area of the fit and averaging over the measurement time interval to yield a count rate. The general trend observed from Fig. 1 is for the Kα emission rate of argon to increase with helium as a mixing gas and decrease with heavier mixing gases. Neon mixing gas produces different trends in the two sources, which remains unexplained. Given that the inner shell ionization rate and Kα emission rate depends on the electron density, argon density and rate coefficient, it is concluded that argon density decreases when the mass of the mixing gas exceeds that of argon. The increase of the Kα emission rate of argon with lighter mixing gases could be due to both the increasing electron density and argon density, the former resulting from increasing total gas density. This assessment is based on the assumption that the rate coefficient for inner shell ionization remains quasi-constant (supported by Ref. [8]) during the mixing gas sweep. Combining the results with heavier and lighter gases it is concluded that the most likely explanation fitting both observations is that the gas mixing affects the density of argon (at constant feed rate), thus favoring the ion cooling explanation. The result also underlines the fact that the diagnostics of the lighter gas could reveal more about the physics of the gas mixing than looking at the heavier gas component in isolation.

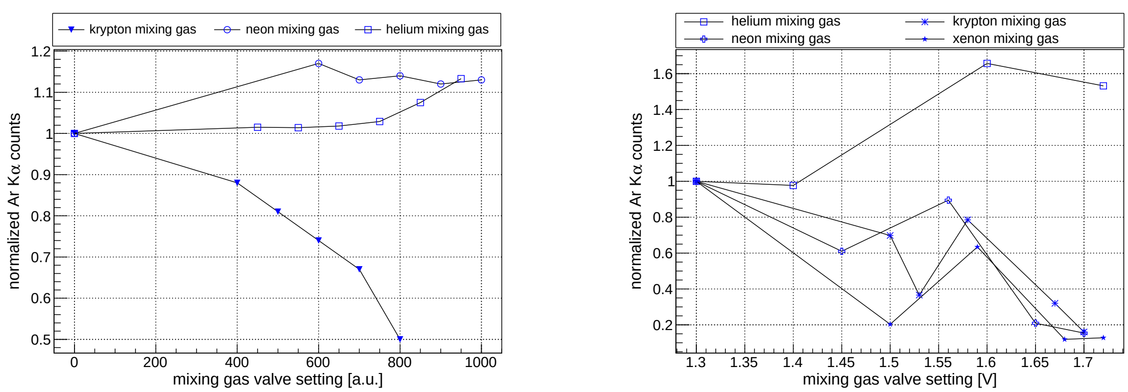

FIGURE 1: Normalized Ar Kα emission / inner shell ionization rates as a function of the mixing gas flow for the 14 GHz ECRIS at JYFL (left) and the GTS at iThemba LABS (right).

The results of the extracted current and the optical emission measurements showed that the inner shell ionization rate and the optical emission intensity of the highest charge states, e.g. Ar^{13+} do not correlate very well. Nevertheless, it was observed that the optical data and beam currents have a better correlation in the case of the highest charge states. Since the inner shell ionization depends on the total argon density, it is reflecting the behavior of the whole population while the optical emission and beam current probe only the specific charge state in question. As an indicator of HCI production the Ar^{9+} beam current is used as this is the first ion produced with an electron removed from the L-shell resulting in a significant increase of the ionization potential in comparison to lower charge states. Furthermore, Ar^{9+} does not suffer from charge exchange reactions as much as the highest charge states, which enables probing the gas mixing effect in a wider range of total pressures. Fig. 2 presents the normalized Ar^{9+} beam current and the normalized Ar^{1+} optical emission, as a function of mixing gas flow rate. Ar^{1+} optical emission is used here as Ar^{1+} beam current can not be measured due to limitation of the bending magnet in the transfer beamline at JYFL. The result clearly demonstrates that the HCI production is accompanied by a modification in the density of the low charge state ions indicated by the decrease/increase of the optical emission signal with lighter/heavier mixing gas, respectively. The results of this investigation demonstrate a strong mass dependence, especially when a heavier gas is introduced into the plasma. This suggest that lowering of the average charge state and ion cooling are the key mechanisms responsible for the effectiveness of the gas mixing. Given that the ionization potential is lower for heavier gases, the increase in plasma density explaining the gas mixing effect can presumably be excluded.

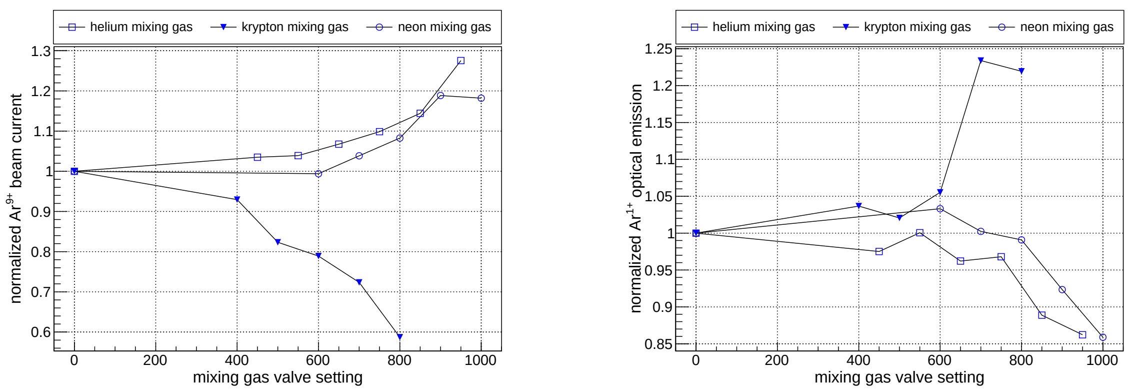

FIGURE 2: Normalized Ar^{9+} beam current (left) and the normalized Ar^{1+} optical emission (right) as a function of mixing gas flow.

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