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The effect of microwave power on the Ar^{9+} and Ar^{13+} optical emission intensities and ion beam currents in ECRIS

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Abstract. The production of Ar^{9+} and Ar^{13+} ions in an ECRIS plasma and the efficiency of the ion beam extraction and transport of the resulting Ar^{9+} and Ar^{13+} ion beams have been studied with the JYFL 14 GHz ECRIS by using optical emission spectroscopy and measurement of the m/q analyzed beam currents. The relative changes in both the optical emission and the ion beam current in CW mode as function of microwave power and in amplitude modulation (AM) operation mode are reported. The results indicate a discrepancy between the parametric dependence of high charge state ion densities in the core plasma and their extracted beam currents. The observation implies that in CW mode the ion currents could be limited by diffusion transport and electrostatic confinement of the ions rather than beam formation in the extraction region and subsequent transport.

INTRODUCTION

The intensities of the ion beams produced by electron cyclotron resonance ion sources (ECRIS) depend on the production rate of the ions and the efficiency of the ion beam extraction and transport. In order to study which one of these is the limiting factor determining the currents of high charge state ion beams, the ion densities (in the plasma) and m/q-resolved beam current must be estimated simultaneously. Such studies have been carried out with optical emission spectroscopy [1] and x-ray spectroscopy [2], both reporting a correlation between the ion densities and extracted beam currents. In Ref. [1] the parametric dependence of the intensities of certain emission lines of metal ions (e.g. Li^{2+} and Mg^{7+}) were correlated with the beam currents of higher charge states (e.g. Li^{3+} and Mg^{8+}). In Ref. [2] the charge state distribution (CSD) of an argon plasma was compared with a typical CSD of the extracted beam measured separately.

The purpose of this work is to study the correlation between the high charge state ion densities in the core plasma and the extracted beam currents by simultaneous observation. We report the microwave power dependence of Ar^{9+} (553.3265 nm) and Ar^{13+} (441.2556 nm) optical emission intensities and extracted beam currents in continuous wave operation mode (cw) and their responses to fast microwave power transients. These emission lines correspond to magnetic dipole transitions between metastable excited state and the ground state; $2s^22p^5\ ^2P^{\circ}_{1/2} \rightarrow 2s^22p^5\ ^2P^{\circ}_{3/2}$ and $2s^22p\ ^2P^{\circ}_{3/2} \rightarrow 2s^22p\ ^2P^{\circ}_{1/2}$ for Ar^{9+} and Ar^{13+}, respectively. There are multiple processes populating the excited states. The main processes are: (i) ionization from $q-1$ charge state ion, (ii) electron - $q+1$ ion recombination, (iii) charge exchange between $q+1$ ion and neutral / low charge state ion, (iv) electron impact excitation and (v) cascade effects from higher electronic states. The relative importance of processes (i-v) on the total population rate of given metastable states are not well known. Due to the metastable state corona equilibrium model cannot be used to describe the population densities. However, based on state-selective cross sections `http://aphysics2.lanl.gov/tempweb/lanl/` and subsequent rate coefficient analysis, we assume that the measured emission intensities are proportional to the total densities of the emitting Ar^{9+} and Ar^{13+} ions without speculating on the predominant excitation channel.

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MEASUREMENT SETUP

The experimental data were taken with the JYFL 14 GHz ECRIS [3]. The plasma was sustained by microwave radiation at the frequency of 14.056 GHz, generated by an analog signal generator (Keysight N5173B EXG) and amplified by a klystron. The given combination allows cw operation as well as tailoring the microwave power pattern in time-domain. The input signal of the klystron was amplitude modulated using a square waveform signal to produce fast transients between 200 W and 530 W output power levels. The ion beam was extracted by applying a voltage of 10 kV and m/q-resolved beam currents of Ar^{9+} and Ar^{13+} were measured with a Faraday cup. The current signal from the Faraday cup was recorded with a combination of a current-to-voltage amplifier and an oscilloscope. The optical emission intensities of Ar^{9+} and Ar^{13+} ions were measured from a radial diagnostics port. The chosen radial line-of-sight between the magnetic poles provides a view through the plasma core surrounded by the resonance zone. The optical measurements were performed with a high resolution (31 pm at FWHM) and high throughput Fastie-Ebert monochromator coupled with a photomultiplier tube detector with a phase-sensitive lock-in detection setup [4]. The data were taken at neutral gas pressures of $4–9{\cdot}10^{-7}$ mbar and at magnetic fields covering the stable operation regime of the JYFL 14 GHz ECRIS. With the parametric sweep it was confirmed that the observed trends can be generalized and also that the 10 kV extraction voltage is sufficient to avoid space charge limited extraction i.e. the beam currents are assumed to be limited by the flux of ions from the plasma to the plasma meniscus (production limited extraction). Only specific examples corresponding to tune for Ar^{13+} are presented hereafter.

RESULTS AND DISCUSSION

The relative changes in both the optical emission and the ion beam current have been measured in CW and amplitude modulation (AM) operation mode. The normalized optical emission signals and the beam currents of Ar^{9+} and Ar^{13+} in cw mode are presented in Figs. 1a and 1b. The result in Fig. 1a demonstrates that the relative change of the Ar^{9+} ion beam current as a function of the microwave power does not necessarily follow that of the optical emission. The ion beam current increases until the microwave power reaches 300 W and then starts to decrease, in contrast to optical emission intensity, which increases monotonically through the microwave power sweep. In the case of Ar^{13+}, a better correlation between the ion beam current and optical emission intensity can be observed as both signals increase monotonically with the microwave power. Similar behavior was observed throughout the probed pressure range.

The effect of a fast microwave power transient with the rise and fall times on the order of 10^{-5} s is presented in Figs. 1c and 1d. With the microwave power of 530 W the Ar^{9+} ion beam current saturates to lower value in comparison to 200 W. On the contrary, the optical emission indicating the density of Ar^{9+} ions in the core plasma first peaks and then saturates to a higher level when the microwave power increases abruptly corresponding to the results of the cw measurement. This suggests that the Ar^{9+} ion density is increasing with the microwave power but the extracted beam current is limited by the ion diffusion from the core plasma to the extraction aperture and/or the ion extraction and transport. The transient peak (and decay) of the optical emission signal implies that the balance in Ar^{9+} production rate is achieved in 40-50 ms, which is the time required for the charge state distribution of the plasma to reach a new equilibrium. In microwave power transition from 200 W to 530 W both the Ar^{13+} ion beam current and optical emission intensity saturate to higher values contrary to the behavior of the Ar^{9+}. The time required for Ar^{13+} optical emission to saturate is approximately the same as for Ar^{9+}. No transient peak of Ar^{13+} optical emission is observed.

Both charge states exhibit a significant afterglow peak of extracted beam current associated with the abrupt decrease of the microwave power while the optical emission decreases to the saturation value at 200 W without a transient peak. This observation suggests that the abrupt decrease of the microwave power releases an already existing population of ions i.e. at the higher microwave power there is a mechanism confining the ions more efficiently than at low microwave power. A possible mechanism is the modification of the electrostatic potential distribution near the plasma core [5], causing a reservoir of ions to build up due to a formation of a potential dip. The observation supports the conclusion that in cw mode the ion currents are limited by diffusion processes and electrostatic confinement of the ions rather than beam formation in the extraction region and subsequent transport. This can lead to discrepancies between the parametric dependence of high charge state ion densities in the plasma and their extracted beam currents as demonstrated above.

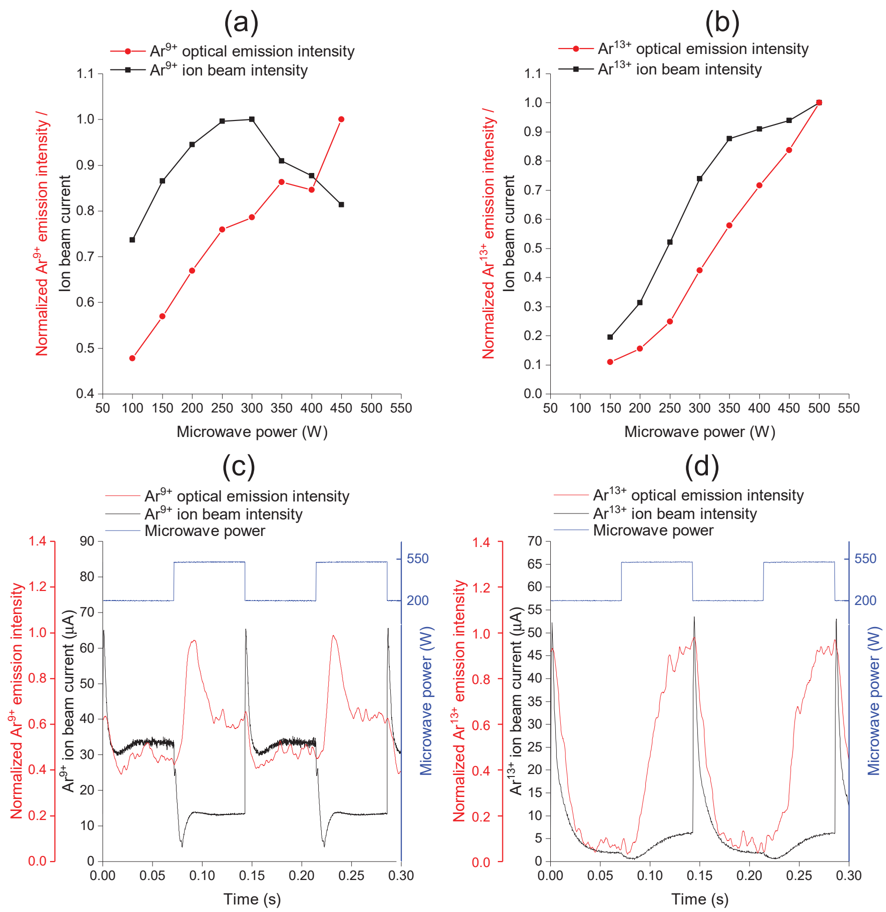

FIGURE 1. Normalized Ar^{9+} (a and c) and Ar^{13+} (b and d) optical emission intensities and extracted beam currents as a function of the 14 GHz microwave power. The upper row depicts the results of the experiment in cw mode while the results of the transient measurement with 7 Hz repetition rate (50 % duty factor) are displayed in the bottom row.

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