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Estimating ion confinement times from beam current transients in conventional and charge breeder ECRIS

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ABSTRACT

Cumulative ion confinement times are probed by measuring decaying ion current transients in pulsed material injection mode. The method is applied in a charge breeder and conventional ECRIS yielding mutually corroborative results. The cumulative confinement time estimates vary from approximately 2 ms–60 ms with a clear dependence on the ion charge-to-mass ratio—higher charges having longer residence times. The long cumulative confinement times are proposed as a partial explanation to recently observed unexpectedly high ion temperatures. The results are relevant for rare ion beam (RIB) production as the confinement time and the lifetime of stable isotopes can be used for estimating the extracted RIB production efficiency.

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I. INTRODUCTION

Doppler broadening measurements[1] have indicated that ions in an electron cyclotron resonance ion source (ECRIS) plasma reach temperatures ≥10 eV—an order of magnitude higher than conventionally thought.[2] The conception of cold (~1 eV) ions is based on the low electron-ion energy equipartition rate and the assumption of short ion confinement times.[2] Ions are collisionally heated by the electrons, and the energy they absorb is limited by their confinement time. However, if the ion confinement time was long, they may absorb enough energy from the cold electron population to explain the observed high temperatures, which motivates this work.

The ion confinement times are probed by a transient method such as previously employed in Refs. 3 and 4. The method is applied in a charge breeder ECRIS (CB-ECRIS) using 1+ injection of potassium and in a conventional ECRIS using radial sputtering of copper. It is argued that the transient method probes the cumulative confinement time of a given particle—i.e., the time it spends within the plasma counting the time spent at different charge states.

II. THEORETICAL BACKGROUND

The balance equation,[2]

$$\frac{\mathrm{d}n^q}{\mathrm{d}t} = +\langle\sigma v\rangle_{q-1\to q}^{\mathrm{inz}} n_e n^{q-1} - \langle\sigma v\rangle_{q\to q+1}^{\mathrm{inz}} n_e n^q$$
$$+ \langle\sigma v\rangle_{q+1\to q}^{\mathrm{cx}} n^{0+} n^{q+1} - \langle\sigma v\rangle_{q\to q-1}^{\mathrm{cx}} n^{0+} n^q - \frac{n^q}{\tau^q}, \qquad (1)$$

defines a group of differential equations describing the time evolution of the ion populations at charge states q. The density is increased by ionizing collisions from lower charge states and charge exchange from higher charge states. Conversely, the density is decreased by ionization to higher charge states and charge exchange to lower charge states. The intensities of these ionization and charge

exchange processes are described by the rate coefficients $\langle \sigma v \rangle_{q \to q'}^{\text{inz/cx}}$. While the first four terms describe ion creation/destruction processes in collisions between ions (n^q) and electrons or neutral atoms (n_e, n^{0+}), the term n^q/τ^q corresponds to ion losses and defines the ion confinement time τ^q. Therefore, measuring the temporal evolution of the ion current yields information on the dynamics of different components of the balance equation.

III. EXPERIMENTAL METHODS AND ANALYSIS

The experiments at the University of Jyväskylä Accelerator Laboratory (JYFL) were conducted on the conventional JYFL 14 GHz ECRIS[5] and at GANIL on the 14 GHz Phoenix-type CB-ECRIS.[6] A support gas plasma discharge was ignited, and another element was injected into the source in pulsed mode. In the conventional ECRIS, the injection of copper was controlled by pulsed, radial sputtering. The on/off pulsing of the sputter voltage was achieved with a fast high voltage (HV) push-pull switch controlling the sample bias similar to Refs. [3] and [4]. In the CB-ECRIS experiments, a 1+ beam[7] of potassium was generated by thermal ion emission, and the pulsing was realized using an electrostatic chopper in the beamline upstream from the charge breeder either deflecting the 1+ beam or allowing it to pass through, thus controlling the material injection into the charge breeder. The 1+ injection allows measuring the amount of injected material, whereas the sputtering yield depends on the applied voltage, the charge state distribution (CSD), and intensity of the ion flux incident on the sample. Both methods allow fast pulsing of material injection.

In the sputtering experiments, the source was operated with 300 W microwave power, a $B_{\text{min}}/B_{\text{ECR}}$-ratio of 0.68, and a negative bias disk voltage of -50 V. The gas feed rate was adjusted to obtain a total extracted current of around 1 mA, where the source extraction and beam transport are known to be efficient. The sputtering voltage was pulsed from zero to -700 V. In the 1+ injection experiments, the source was always tuned for maximum $^{39}\text{K}^{9+}$ current operating around 2×10^{-8} mbar chamber pressure, 250 W microwave power, ΔV of 5 V, $B_{\text{min}}/B_{\text{ECR}}$ of 0.74, and 1+ intensity around 450 nA. The time constant of the linear amplifier used for measuring the nA level currents at GANIL was taken into account in the data analysis by means of deconvolution. The material injection pulse was set long enough for the plasma to reach an equilibrium and extracted currents to saturate—500 ms on with 50% duty factor.

Figure 1 shows an example of $^{63}\text{Cu}^{17+}$ extracted current response to pulsed sputtering in the JYFL 14 GHz ECRIS. The current increases as the neutral copper is stepwise ionized to 17+ and saturates when the different terms in Eq. (1) balance out. The rate coefficients and electron and neutral densities are assumed to be determined by the support plasma alone.

When the material injection is ceased, particle losses and ion production/destruction processes cause the neutral density (or 1+ density for 1+ injection) to diminish. Consequently, the higher state population will also decrease, when the lower state supply runs out, currents of different charge state reacting in sequence. Figure 2 illustrates this process: The higher charge state populations of ^{63}Cu are sustained by the lower ones, and thus their extracted currents begin to decay later. This reasserts the notion that the
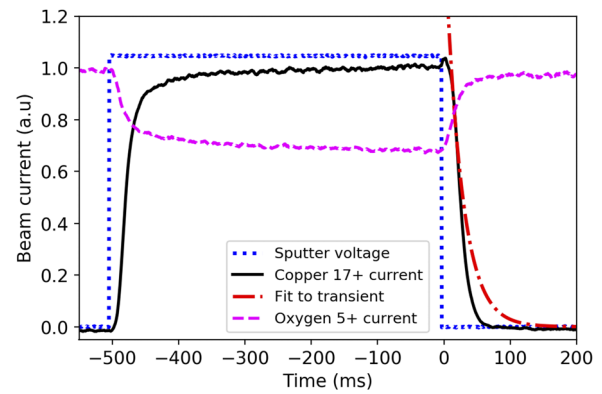

FIG. 1. The extracted $^{63}\text{Cu}^{17+}$ and O^{5+} currents as a function of time (normalized). The red dashed-dotted line is the fit to the transient from 95% to 65% of the $^{63}\text{Cu}^{17+}$ saturation current.

extracted current depends on the ion production rate as well as the confinement time as suggested by Eq. (1).

The decay transient enables defining the cumulative confinement time (τ_c^q) of charge state q as

$$I^q(t) = \bar{I}^q e^{-t/\tau_c^q}, \quad (2)$$

where $\bar{I}^q$ is the saturation current for charge state q. The cumulative confinement time as defined here measures the lifetime-in-plasma of the particles—from the time they are first injected to the moment they are extracted. Due to changing particle densities, Eq. (2) is most accurate at the onset of the transient. The change in plasma conditions is evident from the O^{5+} current in Fig. 1. This perturbation is discussed in Sec. V. τ_c^q is obtained by making a fit to the transient according to Eq. (2), (Fig. 1) showing an example. The fitting range was chosen to be 95%–65% of the saturation current because (i) the onset of the decay best corresponds to the steady-state conditions of the plasma and (ii) the χ^2 value of the fit is found to be best in this region.
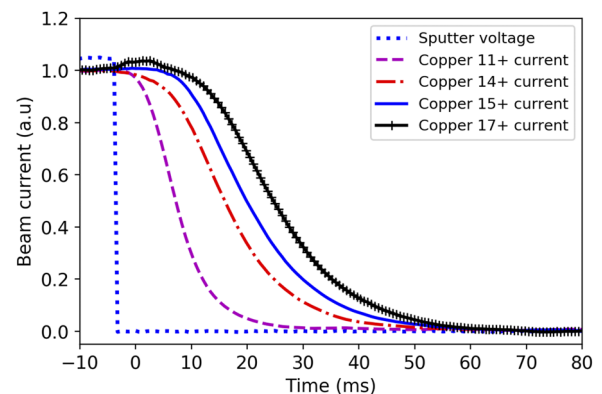

FIG. 2. An example of the extraction currents of different charge states of ^{63}Cu in the sputtering experiments conducted on the JYFL 14 GHz ECRIS. Beam currents normalized to their respective saturation currents.

IV. RESULTS

Figure 3 shows confinement times obtained from the two campaigns as a function of the ion charge-to-mass ratio. The errorbars are standard deviations of the fit. The true uncertainty is determined by the repeatability of the source tuning and is estimated to be 20%–30%. For $Q/M > 0.15$, τ_c^q is greater than 2 ms, increasing with charge state up to 60 ms. The tendency is independent of the material injection method, which validates using conventional ECRIS to study ion confinement in the CB-ECRIS. For $Q/M < 0.15$, the confinement time is less than 1 ms.

Figure 4 displays the confinement time of $^{39}K^{9+}$ ions, as well as the extracted beam current, as a function of B_{min}/B_{ECR}. The maximum 1+/n+ breeding efficiency (4.5%) is obtained at the point of maximum current.

Assuming similar confinement times for a radioactive and stable isotope, the cumulative confinement time allows us to predict charge breeding efficiencies from stable isotope currents as

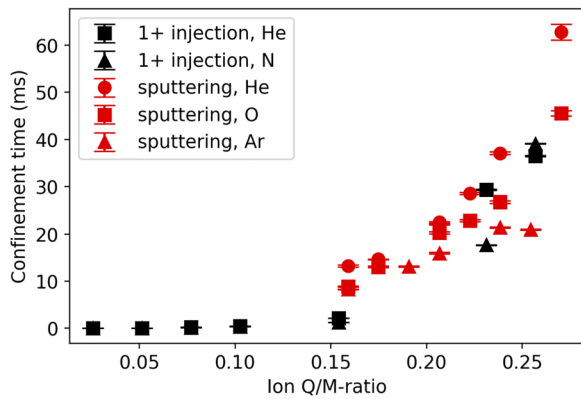$$\frac{\eta_{RIB}}{\eta} = \frac{\bar{I}_{RIB}^q}{\bar{I}^q} = e^{-\tau_c^q \ln(2)/T_{1/2}}, \quad (3)$$

FIG. 3. Cumulative confinement times (τ_c^q) of ^{39}K and ^{63}Cu ions as a function of their charge-to-mass ratio (Q/M) from 1+ injection of potassium into a CB-ECRIS and from sputtering of copper into a conventional ECRIS.
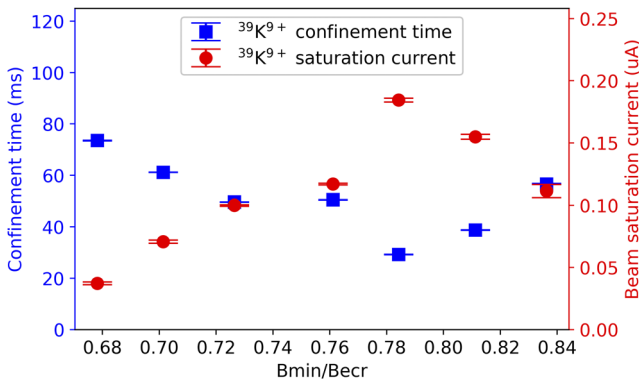

FIG. 4. The confinement time and extracted beam saturation current for $^{39}K^{9+}$ ions in the charge breeder as a function of B_{min}/B_{ECR}.

TABLE I. Predicted 1+/n+ charge breeding efficiencies η and the charge breeding efficiency measured for the stable $^{39}K^{9+}$ at two different B-fields.

Isotope	$T_{1/2}$	η (%)	
$^{39}K^{9+}$	Stable	4.5 (τ_c^q = 29 ms)	2.9 (τ_c^q = 57 ms)
$^{52}K^{9+}$	110 ms	3.7	2.0
$^{53}K^{9+}$	30 ms	2.3	0.8
$^{54}K^{9+}$	10 ms	0.6	0.1
$^{56}K^{9+}$	360 ns	0	0

where η is the charge breeding efficiency and $T_{1/2}$ is the half-life of the radioactive element. τ_c^q estimates the residence time of a particle in the plasma and is consequently the time scale for radioactive decay. Table I shows predicted 1+/n+ charge breeding efficiencies for radioactive isotopes of ^{39}K. The predictions were made using Eq. (3) and two experimental charge breeding efficiencies (4.5% and 2.9% at B_{min}/B_{ECR} of 0.78 and 0.84) corresponding to 29 ms and 57 ms confinement times, respectively. The half-lives $T_{1/2}$ are from Ref. 8.

V. DISCUSSION

It is argued here that τ_c^q—determined as the time constant of the decaying ion current transient—is a measure of *the total lifetime of a particle* in the plasma. It incorporates the particle residence time at different charge states and differs from the conventional confinement time (τ^q) of Eq. (1), which measures *the confinement time of the ion population* having charge state q.

Due to evolving plasma conditions across the transient, the fit overestimates the current at its tail-end. The disturbance to the support plasma is evident from the changing O^{5+} current in Fig. 1. Fitting close to the transient onset thus yields best estimates for steady-state τ_c^q. Minimizing the support plasma disturbance could be achieved by amplitude modulation of the material injection pulse, which will be investigated.

Table II tabulates τ_c^q as a function of the 1+ intensity and sputtering voltage for $^{39}K^{9+}$ and $^{63}Cu^{17+}$, respectively. In the case of 1+ injection, the transient is insensitive to the increase in the 1+ intensity, whereas the transient depends on the sputtering voltage. In addition, the total extracted current was observed to decrease with increasing sputtering voltage. It can be inferred that the sputtering voltage affects the plasma conditions and τ_c^q.

Figures 5(a) and 5(b) demonstrate the effect of sputtering on argon currents. Sputtering aluminum boosts the argon high charge states, while copper suppresses them. This can be explained by gas mixing mass effect,[2] where the light element depletes the heavy element of its kinetic energy improving its confinement. These figures together with Table II indicate that material injection can have a substantial effect on the support plasma, making amplitude modulation preferable. Nevertheless, the obtained τ_c^q values are in accordance with those reported in Refs. 3 and 4. Fast pulsing experiments[9] also indicate that τ_c^q is on the order of tens of milliseconds. The advantage of the fast pulsing method over the transient method is that it is less invasive to the plasma.

TABLE II. The cumulative confinement time of $^{39}K^{9+}$ and $^{63}Cu^{17+}$ tabulated as a function of the 1+ intensity and the sputtering voltage, respectively.

1+ injection:	1+ intensity (nA)	Confinement time (ms)
$^{39}K^{9+}$	145	23
	538	24
	983	25
	1170	26
Sputtering:	Sputter voltage (V)	Confinement time (ms)
$^{63}Cu^{17+}$	−500	35
	−700	28
	−1000	71

In Ref. 10, the ion confinement times were estimated from steady-state beam currents $\bar{I}^q$ with

$$\bar{I}^q = \kappa \frac{(2L)S}{2} \frac{n^q q e}{\tau^q}, \qquad (4)$$
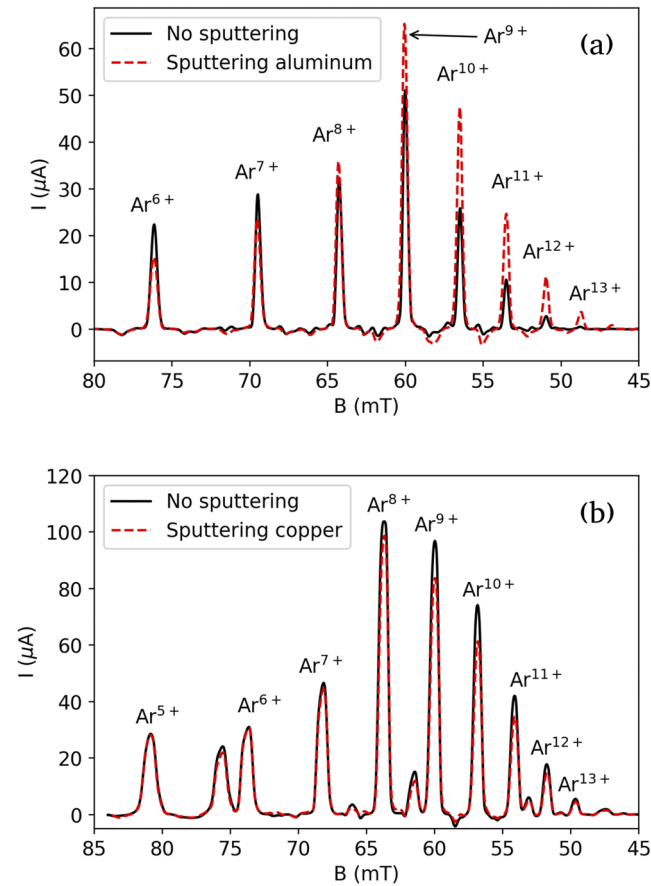
FIG. 5. Effects of sputtering aluminum (a) and copper (b) on argon charge state distribution.

where κ is the beamline transmission efficiency, $2L$ is the plasma length, e is the elementary charge, and S is the area of the extraction aperture. The reported confinement time is less than 4 ms even for the highest charge states of argon. This value presumably represents the confinement time of a given ion population as defined by Eq. (1).

The cumulative confinement time plays a major role in charge breeding. Since τ_c^q measures the total residence time of a particle extracted as an ion at charge state q, it is evident that the feasibility of charge breeding a certain isotope rests on τ_c^q being small compared to $T_{1/2}$. This can be seen from the predicted 1+/n+ efficiencies in Table I. These predictions could be used to test the validity of the transient method for measuring cumulative confinement times. One would first measure τ_c^q for a stable isotope, make predictions for unstable isotopes, and compare to actual charge breeding measurements with rare ion beams (RIBs).

Figure 4 implies that maximizing the extracted current requires τ_c^q to be just long enough to produce the desired ions, i.e., the particle should be ionized to the desired state swiftly and then extracted immediately. This entails maximizing the conventional confinement times and volumetric ionization rates of all lower charge states and minimizing them for the charge state q.

Long τ_c^q values indicate that electron-drag can heat the ions. This was numerically explored in Ref. 1 where electrostatic potential dip confinement[11] was assumed. This scheme yields confinement times according to[12]

$$\tau^q = \frac{R\sqrt{\pi}l}{v_{T_i^q}} \exp \frac{|qe\Delta\phi|}{T_i^q}, \qquad (5)$$

where R is the mirror ratio, l is the characteristic length of the plasma, and $v_{T_i^q}$ is the ion thermal velocity. The ions are trapped in a potential dip generated within the positive plasma potential by the well-confined hot electrons. The ambipolar barrier acts as a cutoff preventing ions from escaping until they reach a threshold energy determined by their charge state and the depth of the potential dip. This causes ions at different charge states to obtain different temperatures regardless of the high ion-ion energy equipartition rate. It was shown in Ref. 1 that using the confinement time of Eq. (5) to approximate the ion energy confinement time and choosing a potential dip depth of $\Delta\phi = 1$ V, the ion temperatures T_i^q resulting from the ion energy balance equation,[2]

$$\frac{dn^q T_i^q}{dt} = \frac{n_e\left(T_e - T_i^q\right)}{\tau_{eq}^{e \to q}} - \sum_{q'} \frac{n^q\left(T_i^q - T_i^{q'}\right)}{\tau_{eq}^{q \to q'}} - \frac{n^q T_i^q}{\tau^q}, \qquad (6)$$

can exceed 10 eV. The time scales $\tau_{eq}^{e \to q}$ and $\tau_{eq}^{q \to q'}$ are determined by the electron-ion and ion-ion energy equipartition rates. In this model, the ion temperature depends on the temperature of the (cold) electron population T_e. The calculation was performed for single component plasma. The code will be refined to include multiple elements and other heating mechanisms. The codependence of the ion temperature and the confinement time prompts the need for experiments to be conducted to study their correlation as a function of the ion source parameters.

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