Commissioning of the DESIREE storage rings - a new facility for cold ion-ion collisions

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Abstract. We report on the ongoing commissioning of the Double ElectroStatic Ion Ring ExpEriment, DESIREE, at Stockholm University. Beams of atomic carbon anions (C^-) and smaller carbon anion molecules (C_2^-, C_3^-, C_4^- etc.) have been produced in a sputter ion source, accelerated to 10 keV or 20 keV, and stored successfully in the two electrostatic rings. The rings are enclosed in a common vacuum chamber cooled to below 13 Kelvin. The DESIREE facility allows for studies of internally relaxed single isolated atomic, molecular and cluster ions and for collision experiments between cat- and anions down to very low center-of-mass collision energies (meV scale). The total thermal load of the vacuum chamber at this temperature is measured to be 32 W. The decay rates of stored ion beams have two components: a non-exponential component caused by the space charge of the beam itself which dominates at early times and an exponential term from the neutralization of the beam in collisions with residual gas at later times. The residual gas limited storage lifetime of carbon anions in the symmetric ring is over seven minutes while the $1/e$ lifetime in the asymmetric ring is measured to be about 30 seconds. Although we aim to improve the storage in the second ring, the number of stored ions are now sufficient for many merged beams experiments with positive and negative ions requiring milliseconds to seconds ion storage.

1. Introduction

The Double ElectroStatic Ion Ring ExpEriment [1, 2], DESIREE, at Stockholm University is in the commissioning stage. DESIREE offers the unique possibility of studying controlled interactions between beams of internally cold ions in opposite charge states with center-of-mass collision energies down to a few meV. This is accomplished through the construction of two racetrack shaped electrostatic ion-storage rings with circumferences of 8.6 m sharing a common

straight merging section. The experiment is contained in a series of enclosures which, ordered from out to in, are: an outer steel vacuum chamber kept at room temperature and with a vacuum near 10^{-8} mbar, an intermediate copper heat shield at below 50 K and an inner aluminum vacuum chamber. The latter houses the electrostatic elements of the two storage rings and detectors and is currently at a temperature of 13 K. The physical pressure inside the inner chamber is measured indirectly to be about 5×10^{-14} mbar [3]. A more in-depth description of DESIREE is given in references [1, 3].

Early electrostatic ion traps showed that compact, table-top devices such as the Zajfman trap [4] and ConeTrap [5] could be used to store beams of keV ions to study interactions with lasers or to measure inherent fragmentation and decay behaviors of atomic, molecular or cluster ions. The long storage time makes it possible for the ions to cool internally until they assume the same temperature as the storage device. Storage at cryogenic temperatures, with strongly reduced black body radiation and with the effects of cryo-pumping, opens up the option to study also very weakly bound systems such as a large range of anions and long lived metastable states. This was demonstrated for lifetime studies of metastable He^- with the ConeTrap set-up cooled to 10 K [6]. In parallel to the development of these compact devices, electrostatic ion storage rings have been developed, the first one being ELISA (Electrostatic Ion Storage ring in Aarhus) in Denmark [7]. Electrostatic storage ring design have similar advantages as the electrostatic ion-beam traps but in addition they have much higher capacity in terms of the number of stored ions and further, the ions have the same kinetic energy during the whole storage cycle and allow for easier access to the ion beam and its various reaction products. A number of electrostatic storage rings have been or are presently in use or under different phases of development around the world: the Tsukuba electrostatic storage ring [8], the TMU (Tokyo Metropolitan University) [9] and RIKEN [10] rings in Japan; the Mini-Ring in Lyon, France [11]; the CSR (Cryogenic Storage Ring) in Heidelberg, Germany [12]; the FLSR (Frankfurt Low-energy Storage Ring) in Frankfurt, Germany [13]; SAPHIRA (Storage ring in Aarhus for PHoton Ion Reaction Analysis) in Aarhus, Denmark [14]; and the electrostatic storage ring at King Abulaziz City of Science and Technology in Riyadh, Saudi Arabia [15]. With DESIREE we combine the advantages of electrostatic storage rings with operation of two rings at cryogenic temperatures.

The two storage rings in DESIREE have different layouts; a ring with symmetrically distributed focusing quadrupole doublets (green rectangles in figure 1) and the other with an asymmetric design with respect to the placement of the quadrupole doublets. The different designs allows two ion beams of the same velocity with a mass ratio of up to 20:1 to be stored at the same time - the heavier ions in the asymmetric ring and the lighter ions in the symmetric ring (cf. [1, 3] for details). This is a requirement for the planned merged beams experiments where the beams overlap in their common straight section. The first storage of ion beams in the symmetric ring of DESIREE was presented by Schmidt *et al.* [3] earlier in 2013. There it was reported that ion beams of 10 keV C^- and C_2^- were stored in the symmetric ring with lifetimes of several minutes. In this special report we present additional results from the ongoing commissioning of DESIREE including the first results from the storage of ions in the asymmetrical second ring as well as a study of the storage capability as a function of ion beam intensity in the symmetric ring.

2. Experiment

Atomic and molecular carbon anions (the storage of C^- and C_4^- are discussed in this paper) are produced in a cesium sputter ion source and accelerated to 10 or 20 keV. The ion beams are mass selected using a 90° bending magnet before being chopped into ion bunches of 10 μs duration. The beam is then transported through a series of electrostatic steering and focusing elements to either of the two DESIREE storage rings. One set of deflectors in each ring is connected to a high voltage switch which allows for rapid switching between injection and storage settings for

the ring before the ion bunch makes the first full revolution. The revolution time of 10 keV C^- is 21.6 μs.
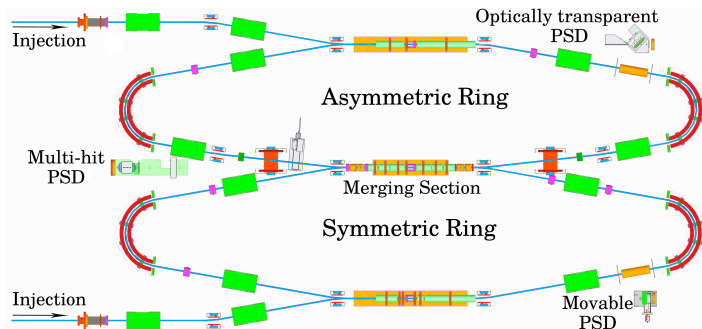

Figure 1. Layout of the electrostatic elements, detectors and ion beam trajectories of DESIREE. Ions are injected from the left in the figure and stored in the closed rings. Well determined fractions of neutrals created in collisions with the residual gas hit the position-sensitive detectors (PSDs) following the straight sections. A description of the components are given in references [1, 3, 16].

Examples of possible experiments with DESIREE include the measurement of intrinsic lifetimes of metastable states in positive and negative atomic ions, studies of mutual neutralization, charge exchange in collisions between anions and cations, and bond formation down to very low energies. DESIREE also opens up new opportunities for studies of cluster relaxation and stability and reaction kinetics for astrophysics and atmospheric science.

The experiments presented here represent the first stages of commissioning of the individual rings. As a means of understanding their characteristics and determining the optimal settings for each ring, an ion bunch is injected and stored and the rate of neutrals leaving the ring is measured as a function of time by various position-sensitive detectors (PSDs) following the straight sections of the rings (cf. fig. 1). The anions are neutralized through electron detachment in collisions with the residual gas in the vacuum chamber.

3. Results and Discussion

3.1. Thermal Load

DESIREE is cooled to cryogenic temperatures using four Sumitomo two-stage cryocoolers with the first and second stages mounted to the copper shielding and aluminum inner vacuum chamber respectively. Prior to installation, the cooling power of the cryocoolers were tested in a controlled test chamber environment [1] with the resulting cooling power shown as a function of temperature for the two stages in figure 2. At present both stages are at stable temperatures with the cold heads at 48 K and 7.5 K (green rings in figure 2), corresponding to total cooling power by the four combined cryocoolers of 180 W and 32 W on the copper heat screen and on the inner vacuum chamber, respectively.

3.2. Ion Storage Capability

At room temperature, the rest gas pressure in DESIREE is of the order 10^{-8} mbar. At these conditions collisions between the ion beam and the residual gas dominate the ion loss and we measure single exponential decays for 10 keV stored C^- beams corresponding to $1/e$ lifetimes of approximately 5 ms (cf. figure 2 in ref. [3]). When we decrease the temperature and thus the residual gas density in the inner vacuum chamber there is a dramatic change in the shape of the decay curve. Figure 3 shows the count rate of neutral products leaving the ring when a beam of 10 keV C_4^- ions is coasting at 13 K. During the first 300 seconds, there is a rapid non-exponential loss of intensity before the decay approaches an exponential behavior. At later
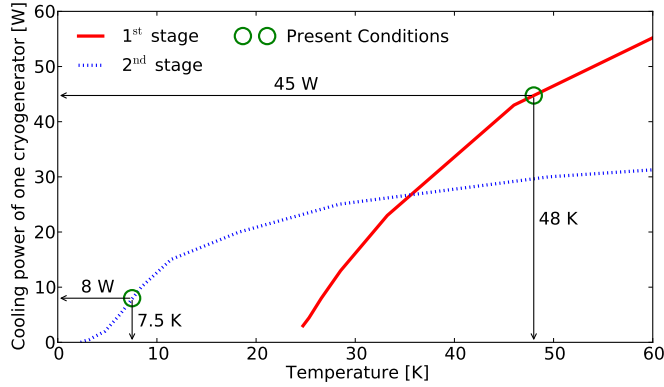
Figure 2. Cooling power as a function of temperature for the two stages of the cryocoolers used on DESIREE (curves), with present operational temperatures (open circles) on the 2nd stage (cooling the inner chamber) and the 1st stage (cooling the screen).

times the decay is thus predominantly of exponential character. A low constant background count rate due to detector dark counts has been subtracted from the data shown in figure 3.
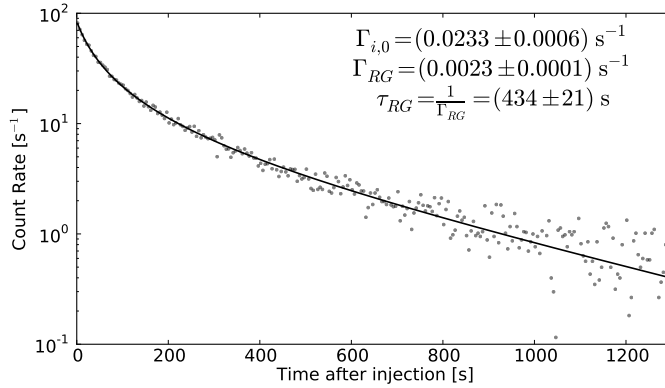

$$\Gamma_{i,0} = (0.0233 \pm 0.0006)\ \text{s}^{-1}$$
$$\Gamma_{RG} = (0.0023 \pm 0.0001)\ \text{s}^{-1}$$
$$\tau_{RG} = \frac{1}{\Gamma_{RG}} = (434 \pm 21)\ \text{s}$$

Figure 3. Count rate of neutral products from a 10 keV C_4^- ion beam interacting with the residual gas (RG). The rest gas limited lifetime τ_{RG} is longer than 7 minutes. The parameter $\Gamma_{i,0}$ is explained in the text and the full line shows a fit to the experimental data using eq. 3 (cf. text).

We model the decay profile shown in figure 3 by means of the same approach as was successfully used earlier for ConeTrap [5, 6]. The total decay rate $\Gamma(t)$ is assumed to consist of the sum of two components: Γ_{RG}, the constant loss rate due to neutralization of the beam in collisions against the residual gas and Γ_i, which is the rate of loss due to the interaction between the ions (i) and the space charge of the ion beam itself. The latter term is assumed to be proportional to the number of ions stored, $N(t)$, which decreases with time t. The time dependence of the total loss rate is thus

$$\Gamma(t) = \Gamma_{RG} + \Gamma_{i,0}\frac{N(t)}{N_0} \tag{1}$$

where N_0 is the initial number of stored ions at $t = 0$ and $\Gamma_{i,0} = \Gamma_i(t = 0)$ is the initial loss rate induced by the space charge of the ion beam. The number of stored ions is then obtained from

$$\frac{dN(t)}{dt} = -\Gamma(t)N(t) = -\Gamma_{RG}N(t) - \Gamma_{i,0}\frac{N(t)^2}{N_0} \tag{2}$$

with the solution

$$N(t) = \frac{N_0}{(1 + \Gamma_{i,0}/\Gamma_{RG})e^{t\Gamma_{RG}} - \Gamma_{i,0}/\Gamma_{RG}}. \tag{3}$$

This expression gives an excellent fit to the experimental data in figure 3. The initial loss rate due to the space charge ($\Gamma_{i,0}$) is an order of magnitude greater than the corresponding rest gas

limited rate (Γ_{RG}) in this case. Only when the intensity of the beam has dropped to below about one tenth of its initial value does the residual gas limited rate dominate. The factor $e^{\Gamma_{RG}t}$ in the first term of the denominator of eq. 3 grows exponentially with time and thus $N(t) \propto N_0 e^{-\Gamma_{RG}t}$ for sufficiently large values of t even when $\Gamma_{RG} << \Gamma_{i,0}$. The actual number of ions stored in the ring $N(t)$ is proportional to the count rate and a typical injected ion bunch initially contains over 10^6 ions [3].
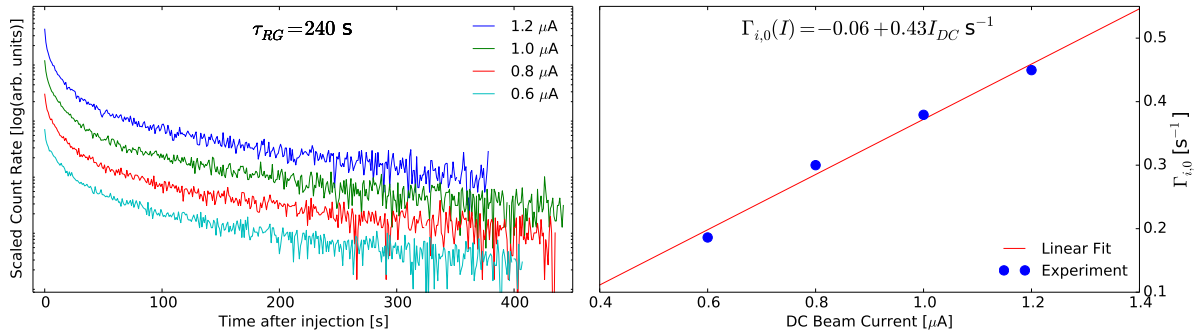

Figure 4. Count rates measured with four different injected ion beam currents of 10 keV C$^-$ in the symmetric ring at 13 K (left). The decay rate component arising from the space charge of the beam, $\Gamma_{i,0}$, decreases linearly in the range studied here (right) while the residual gas limited lifetime remains unaffected at $\tau_{RG} = 240 \pm 10$ seconds. The uncertainties of the measurements in the right panel are smaller than the data points. Following the initial rapid loss of ions due to the space charge effect, the count rates approach the same value, regardless of the injected ion current. The four curves in the left panel have been displaced vertically as they otherwise fall on top on each other except at the shortest times.

We have measured the relation between the loss rate due to the interaction with the ion beam space charge at injection and the injected ion beam current. For each of the four measurements we also extracted the decay rate due to collisions with the residual gas. Figure 4 shows the results when the beam intensity is varied by up to a factor of two. Here the intensity of the beam is measured as a DC current in a Faraday cup just before the DESIREE chamber, a 10 μs pulse of this beam is then injected into the ring and stored for up to 30 minutes. We observe that the initial loss rate, $\Gamma_{i,0}$, due to the space charge deceases linearly while Γ_{RG} and thus the rest gas limited lifetime remain constant at $\tau_{RG} = 240 \pm 10$ seconds. Note that the space charge effect will cause ions in the beam to leave the acceptance for storage in the ring without being detected. The constant loss rate gas collisions on the other hand results in neutral products which continue with practically the same velocity as before the collision and a large fraction of the neutralization events along the straight sections will produce neutrals that reach the detectors.

3.3. The Asymmetric Ring
The second ring in DESIREE, the asymmetric ring, is currently undergoing commissioning work. As with the previously discussed experiments with the symmetric ring, bunches of 10 keV C$^-$ ions have been stored in the asymmetric ring. The count rate for such an experiment is shown in figure 5. There is a significant difference in the fitted parameters when comparing results from the two rings, the lifetime for 10 keV C$^-$ in the symmetric ring being $\tau_{RG} = 263 \pm 7$ seconds [3]. The decay rate attributed to the space charge is significantly larger and the lifetime is much shorter in the asymmetric ring. Since both rings share a common vacuum chamber with identical environmental conditions, the residual gas limited lifetimes in both of the rings

are expected to be practically identical. As this is clearly not the case we conclude that some unknown factor is inducing a loss of beam intensity at a rate higher than what is caused by rest gas collisions and hence there is still work to be done in finding optimal settings of ion-optical lenses and steerers for storage in the asymmetric ring.
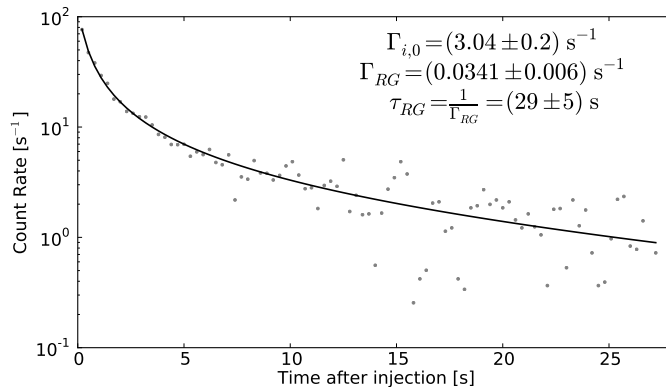

$$\Gamma_{i,0} = (3.04 \pm 0.2)\ \text{s}^{-1}$$
$$\Gamma_{RG} = (0.0341 \pm 0.006)\ \text{s}^{-1}$$
$$\tau_{RG} = \frac{1}{\Gamma_{RG}} = (29 \pm 5)\ \text{s}$$

Figure 5. Neutral count rate for a beam of 10 keV C^- stored in the asymmetric ring of DESIREE. The observed lifetime is significantly shorter than in the symmetric ring, compare with figure 3 and thus not only a result of collisions with the residual gas (cf. text).

4. Conclusions and Outlook

Both rings in DESIREE are operational and millions of ions may be stored in both of them. At the current operational conditions at $T = 13$ K the thermal load of the copper heat shield and inner aluminum vacuum chamber are 180 W and 32 W respectively. Residual gas limited lifetimes for the storage of keV carbon anions in the symmetric ring are measured to be over seven minutes. The ion loss rates consist of two components: a time dependent rate proportional to the intensity of the beam caused by the interaction of ions with the space charge of the beam itself and a constant rate due to neutralization of the charged ions due to collisions with the residual gas. The first term is observed to have a linear dependence on the number of stored ions in the currently investigated intensity range. Further experiments at lower beam intensities are required to fully investigate this effect.

Ion beams have also been stored in the asymmetric ring. So far the storage lifetimes in the asymmetric ring are significantly shorter than those in the symmetric ring. Further optimization of the storage parameters for the asymmetric ring are required to reach a residual gas limited storage lifetime. Following the ongoing commissioning of the asymmetric ring the facility will be fully operational and the first merged beams experiments with meV collisions between positive and negative ions can be undertaken.

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