STATUS OF DESIREE

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Abstract

DESIREE [1] is a double electrostatic storage ring in a cold (13 K) environment with an excellent vacuum. Very long storage times in both rings have been achieved, which has enabled the preparation of beams in a single quantum state. The status of DESIREE is presented with particular emphasis on measurements of stored beam currents in the sub-nA range. We also discuss the ongoing work towards stochastic cooling of very slow beams.

INTRODUCTION

The DESIREE storage ring facility is located at the Physics Department at Stockholm University. It consists of two electrostatic storage rings with one common straight section. The rings are cooled to around 13 K. The two rings are slightly different; to be able to merge two beams with the same velocity and different masses two extra pairs of horizontal steerers are needed in ring A (asymmetric). The space needed for these steerers requires two quadrupole pairs to be displaced compared with ring S (symmetric). The asymmetry and the large distance between the quadrupoles make the beam optics in ring A more difficult to handle than in ring S.

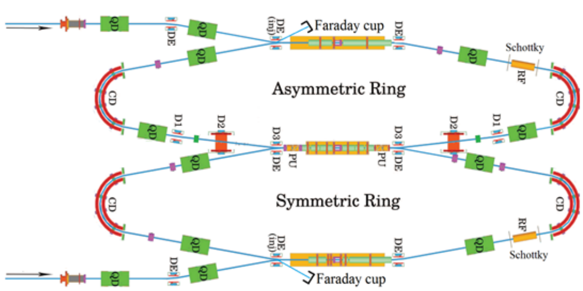

Figure 1: Top view of DESIREE with the positions of Fara- day cups and Schottky detectors indicated. Each ring is 8.6m in circumference.

First beams were stored in ring S in October 2012 and in ring A in April 2013. All published experiments have been made with anions in ring S, but we will focus more on two-ring experiments after recently completed detector replacements and upgrades.

BEAM CURRENT MEASUREMENTS

Ion-beam injection and storage in DESIREE is handled by switching the polarity of a 10° bend before injection, and then back again before the injected beam has made one revolution. An advantage of this method is that the circulating beam is dumped in a Faraday cup placed on the outside of the ring at the end of the machine cycle. The positions of the cups are shown in Fig. 1. There are filters on all HV supplies to avoid noise heating the beam,

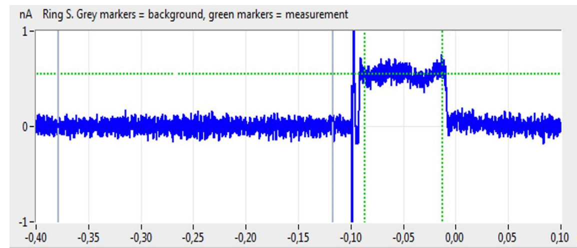

Figure 2: Current vs time in the Faraday cup for a 10 keV C_3^- beam averaged over 10 cycles. The current in the dump is measured between the green markers, while zero is defined by the average between the grey markers. At -0.10 ms we see noise from the switch of the injection power supply.

but the filters on the injection bends are disconnected during the fast switching phase.

The measurement of the current in the beam dump is now a main diagnostic tool for optimization of transport, injection, and storage. We often use automatic optimization for setting up DESIREE, and optimization on the single shot current in the beam dump works very well for currents larger than 1 nA. It also is most useful for surveillance of running experiments. Figure 2 shows the signal from the dumped beam on a Faraday cup.

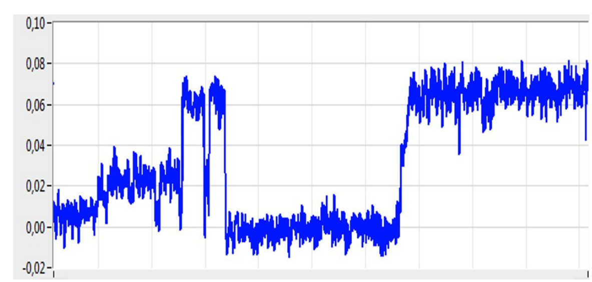

Figure 3: Current of 10 keV C_{60}^- in the beam dump (0-0,07 nA), averaged over 10000 cycles. Each point is the moving average of 20 cycles.

Data is collected with a 20 MS/s/ch Agilent L4534A digitizer and processed with a LabVIEW program, which handles e.g. averaging and offset subtraction with the possibility to also use digital filtering. The latter is done by increasing the measuring time to 20 ms (which gives 50 Hz frequency resolution), followed by a Fourier transform, remove selected frequencies, and finally make an inverse Fourier transform. Even though the uncertainty in the current measurement may be significantly reduced using this method, it takes 0.6 s on the PC and is not always used as it limits the speed of the automatic optimization. Figures 2 and 3 show data taken without using the filter.

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With a large number of averages, or with the filter and a smaller number of averages, the resolution is a few pA.

The Fast Faraday Cup Signal Amplifier

The current from the Faraday cup is amplified using a two-stage amplification with a 2 MΩ transimpedance amplifier (LT1806) and an inverting post-amplification with a gain of 50. A feedback capacitance of 0.5 pF compensates for the input capacitance, while the maximum trans-impedance is limited by the speed requirement of the amplifier. It is important to note that the total amplifier noise is dominated by the input voltage noise gain at high frequency [2], which is given by the ratio between the Faraday cup stray capacitance and feedback capacitance typically of 100-1000 pF. Therefore, another low-noise JFET gain stage using a BF862 with a voltage noise density of about 0.8 nV/√Hz was added similar as described in [3].

SCHOTTKY SIGNALS AND BEAM LIFETIMES

The lifetimes of the beams in DESIREE can be quickly estimated by measuring the current in the beam dump after a few cycles with varying cycle lengths. The most accurate measurement is probably with particle detectors, but this method is only practical with stored negative ions at the extremely low residual gas pressure in DESIREE. For positive ions, the rate of neutrals produced by collisions with the residual gas is too small. Here we will discuss measurements with the Schottky detectors, 0.4 m long tubes that also can be used with a small RF signal to bunch the beams.

In a plot as Fig. 4 of the Schottky signal squared vs frequency the area is proportional to the number of circulating ions and the current. To calculate the beam lifetime, we fit the Schottky area (or current) as a function of time to the equation

$$I(t) = \frac{I(0)}{\left(1+\frac{Arg}{Ai}\right)e^{t\,\mathrm{Arg}}-\frac{Arg}{Ai}}, \quad (1)$$

where $1/A_{rg}$ is the residual gas limited lifetime and A_i is the rate of ions lost due to ion-ion interactions [4]. This equation describes the number of stored ion as a function of time for a beam with a constant probability of losses due to collisions with a residual gas molecule and with additional losses that depend on the number of stored ions.

Using the Schottky method, some of the longest beam lifetimes we have achieved in DESIREE were measured for stored Xe^+ ions at 10 keV. These measurements are shown in Fig. 5. Nevertheless, it is difficult to make a reliable fit of the rest gas component both since the measuring time is only slightly longer than the rest-gas limited lifetime and since the ion-ion effect is important during the whole cycle. After 3600 s the lifetime of the beam in ring S is 2000 s, still significantly lower than the rest gas limited lifetime, and after 1200 s the lifetime in ring A is 670 s. It is reasonable to expect a shorter lifetime in ring A with its much smaller dynamical aperture. The reason for this is that the two extra steerers in ring A make it necessary to increase the distance between the quadrupole doublets beyond their optimal positions. Thus, the lifetime will be shorter even if the pressure is the same in both rings. In this case, however, the pressure was lower during the measurement in ring S since we did a "micro-bakeout" to 30 K improve the vacuum before the run.

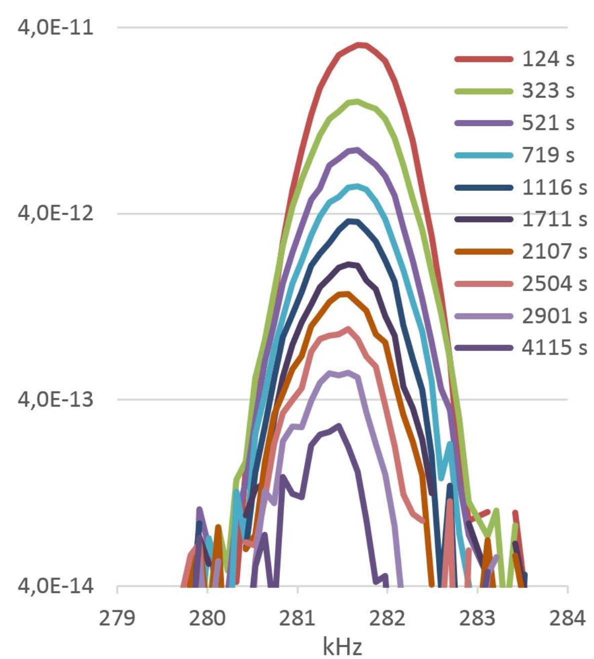

Figure 4: Schottky signal squared vs frequency in ring S. The signal can be followed for more than an hour. 10 keV Xe^+ at the 20th harmonic with background subtracted and the injected current is around 7 nA. The numbers in the legend show the average time after injection. With time one sees a slight decrease of the average frequency but very little frequency broadening.

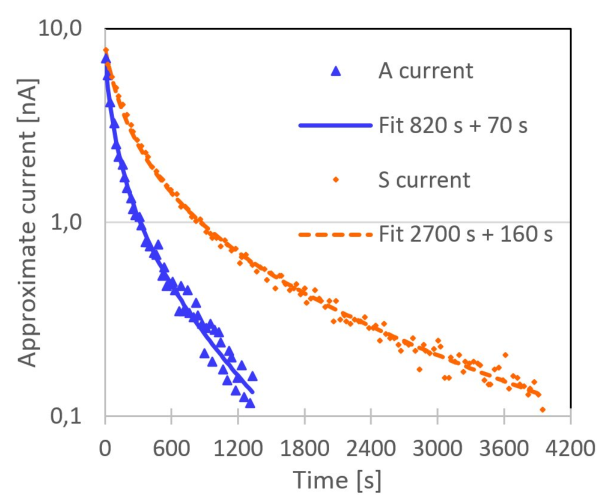

Figure 5: Current of 10 keV Xe^+ in both rings, estimated from the Schottky area for one measurement in each ring. The lines are fits to Eq. (1) with $1/A_{rg}$ and $1/A_i$ given in the legend.

SINGLE QUANTUM-STATE BEAMS

The long storage lifetimes of the beams in DESIREE make it possible to study how the population of the rotational states in molecules reaches thermal equilibrium [6]. The characteristic relaxation times for rotationally excited molecules are of the order of hundreds of seconds [7], which makes DESIREE well suited to study this relaxation. The populations of the various rotational states for an ensemble of OH^- ions stored in the S ring were measured as a function of storage time by means of a laser probing technique. Figure 6 shows an example of a measurement of the currents of the ions in different rotational states vs. time. The injected current was about 3.5 nA, corresponding to about 600 000 ions. After about 10 minutes of storage an equilibrium distribution is reached with 93.3±0.6% of the ions in their lowest quantum state (the rotational ground state of the lowest vibrational state in the electronic ground state). By applying a continuous laser for 450 s to actively deplete the stored ion beam from all the ions in the rotational states above the ground state (J≥1) and then letting these states repopulate again, an even lower equilibrium population of the J=0 state of

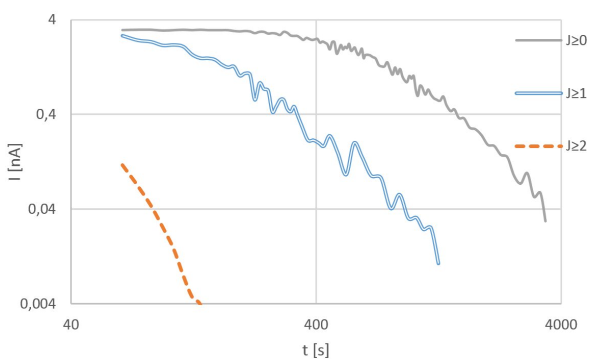

Figure 6: Estimated OH^- current in different rotational states vs. time.

94.9±0.4% was obtained, corresponding to a temperature of 13.4±0.2 K. The difference between the two measurements is ascribed to the elimination of a contamination in the beam consisting of ^{17}O.

The temperature of the stored ion ensemble is consistent with the temperature of the vacuum chamber (13.5±0.5 K). When designing DESIREE, great care was taken to avoid exposure of the stored ions to any blackbody radiation from surfaces that are warmer than the cold surroundings of the inner chamber. The measured temperature of the stored ions indicates that the design has been successful. We also conclude that any other possible source of excitation such as excitations in collisions with residual-gas molecules is essentially negligible.

The fact that the ions reach a thermal equilibrium with the rings and their chamber is a general result and any infrared active molecular ion would reach such low temperatures. This is a most important result as it opens avenues to control and manipulate the quantum states, or quantum state distributions, for various experimental studies as for example merged beams studies. Using the method of active depletion with a continuous laser a 99% pure rotational ground state beam was obtained.

STOCHASTIC COOLING

At DESIREE development of stochastic cooling is currently in progress. The cooling system uses the filter method for momentum cooling with a periodic notch filter with notches at every harmonic of the revolution frequency. Because of the notch filter particles with correct momentum does not receive a correction while slow particles are accelerated and fast particles are decelerated, resulting in a beam with smaller momentum spread. Following the approach in [8], we have developed a digital notch filter using a Kintex-7 KC705 FPGA. It allows for changing the notch frequency on the fly. An adjustable delay is also implemented into the FPGA. It is crucial to have the correct timing between pickup and kicker and this has been successfully tested by measurement of the beam transfer function.

The cooling project is currently in an early stage and while it has been tested no cooling has yet been achieved. A major challenge is to obtain a low noise pickup signal across a wide enough frequency range. At present we aim at the frequency band 100-1500 kHz. The long storage times of Xe^+ ions described above could make them a good candidate for cooling. They are estimated to have a cooling time of about one minute, a value which should be considered as a lower limit.

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