THE CRYOGENIC STORAGE RING CSR

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Abstract

The CSR is a cryogenic electrostatic storage ring located at MPI for Nuclear Physics in Heidelberg. The CSR is designed to perform experiments on ions stored in a low thermal radiation field ($\approx$ 10 K) and in ultra high vacuum conditions. The experimental vacuum system of the CSR, together with all ion optical elements, is entirely housed in a cryostat. On March 17, 2014 a 50 keV Ar^+-beam, delivered from the new electrostatic ion accelerator platform was successfully injected and stored in the CSR at room temperature. The ion beam storage was an important mile stone in verifying the optical design and high-voltage stability. In spring 2015, the complete CSR was cooled to an average temperature below 10 K and first experiments with stored atomic and molecular ions have been successfully performed. We discuss the layout and first operation with a focus on ion beam diagnostics.

Figure 1: The cryogenic storage ring CSR with 35 m circumference.

INTRODUCTION

The CSR shown on Fig. 1, is a fully electrostatic storage ring used to store atomic, molecular and cluster ion beams [1] in the energy range of q·(20-300) keV, where q is the charge state of the ions. The whole storage ring can be cooled down to temperatures of only a few Kelvin where the stored molecular ion beams reach their lowest quantum states. This very low temperature also creates an extremely high vacuum. In fact, observations in the first cryogenic operation indicate residual gas densities below 20 molecules/cm^3. Cooling all ion optics and the vacuum enclosure to 10 K also provides the benefit of a uniquely low level of blackbody radiation in studies with molecular ion beams. In March 2014, to demonstrate the functionality of the CSR, a 50 keV $^{40}Ar^+$ beam was stored for hundred of turns in the ring under room temperature conditions. The complete storage ring was not yet cooled or baked-out at this time, a vacuum in the 10^{-7} mbar range was obtained, limiting the storage life times for singly charged ions to the order of a few milliseconds. In 2015, the storage ring was cooled down to an average temperature below 10 K. At this temperature lifetimes for singly charged ions up to 2500 s have been achieved. A detailed report of the first cryogenic operation of the storage ring will be given in an upcoming publication.

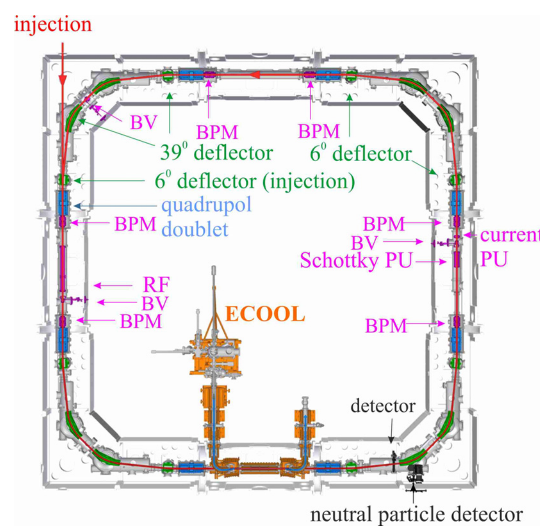

Figure 2: Layout of the cryogenic storage ring CSR. The diagnostics are marked in purple color, it means: BPM-horizontal and vertical beam position monitor, BV-beam viewer, PU- pick-up, RF-rf-system.

LAYOUT

The circumference of the storage ring is approximately 35 m. The beam optical elements consist of two quadrupole families, 6° deflectors to separate the ion beam from neutral reaction products and 39° deflectors (Fig. 2). In the current configuration it is possible to merge the ion beam with laser beams. The remaining experimental straight sections will contain an electron cooler and a reaction microscope for reaction dynamics investigations, respectively. The last remaining linear section is uniquely reserved for beam diagnostics, which contains a beam viewer for the first turn

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diagnosis, a Schottky pick-up and a current monitor to measure the intensity of bunched ion beams (see Fig. 2).

CRYOGENICS

The CSR consists of 16 cryostat chambers with a cross section of about 1 m by 1 m [1], three at each corner and one for each straight section. The outer chambers provide the insulation vacuum of 10^{-6} mbar to ensure thermal insulation of the inner vacuum chamber containing the storage ring ion optical elements (Fig. 3). The inner vacuum chamber is surrounded by two radiation shields, where the inner radiation shield is held by titanium supports to the inner vacuum chamber. The lower part of the 40 K shield is carried by a specially designed support structure made from corrugated titanium sheet mounted inside the outer chamber. The rectangular 80 K sheets is suspended from the 40 K base plate by inconel wires. Thirty layers of multi-layer insulation around the 80 K shield are used to reduce the heat load from the outer chamber walls. For baking of the inner vacuum chambers, which is important for room temperature operation, the 80 K shield is equipped with copper tubes for water cooling to prevent destruction of the outer multi-layer insulation at temperatures above 100 °C. The supply lines for liquid helium to the cryogenic chambers are mounted inside the 40 K shield.

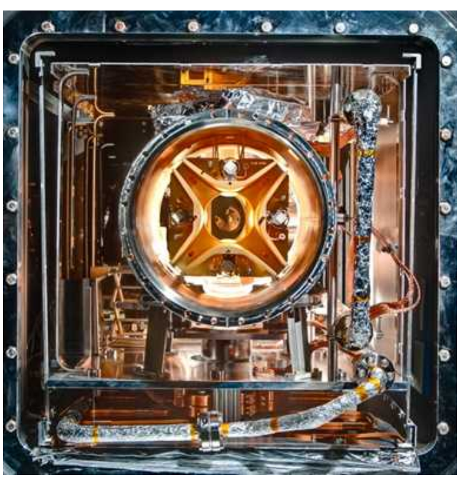

Figure 3: View along the ion beam path into a cryogenic quadrupole unit of the CSR. The electrodes in the center are surrounded by the cryogenic vacuum chamber, refrigerant tubes, and two radiation shields with the inner one serving as a mechanical chassis held at 40 K.

ION BEAM DIAGNOSTICS

The ion currents envisaged for operation of the CSR lie in the approximate range from 1 nA - 1 μA. The resulting low signal strengths on the beam position pickups, current monitors and Schottky monitor require strong demands for the diagnostic tools. For the first turn diagnostics in the CSR, three destructive low intensity beam viewers are used to detect a low intensity injected ion beam [2, 3]. The beam viewers consist of an aluminum plate on which secondary electrons are produced when hit by ion beams. Using a grid the electrons are extracted and accelerated towards a 40 mm MCP/phosphorous screen combination. The image of the beam is recorded via a CCD camera. Two rotary feedthroughs are used to move the aluminum plate. For monitoring of stored beams during the first few turns, a pulse length less than the revolution time must be injected into the ring. The dc current from the ion source is pulsed via a chopper before the beam injection. In combination with the switching of the first 6° deflector,seen by the ions when entering the storage ring, pulses of desired temporal length can be injected and stored. With our current pick-up, a 3.5 cm long tube, we are able to measure the number of injected and stored singly charged ions down to $\approx 10^6$. Every time the circulating ion pulse passes the pick-up a voltage signal, discussed in [4], is induced. The measured pick-up signal for a stored $^{40}Ar^+$ (E=60 keV) ion beam is shown in Fig. 4. An absolute measurement of the stored ion number is possible by integration of one measured ion pulse. From the measurement shown in Fig. 4 an injected ion number of $8.5 \cdot 10^7$ is derived. The current monitor can be used

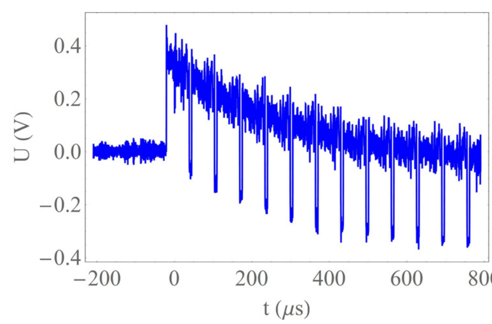

Figure 4: Measured current pick-up signal as a function of time for $^{40}Ar^+$ ions (E=60 keV).

for beam detection until the injected ion beam pulse loses its time structure due to the momentum spread. With the Schottky pick-up it is possible to detect a coasting beam by measuring the Schottky noise of the stored ion beam. Fig. 5 shows the measured Schottky power of a stored Co_2^- ion beam at different times after injection. The Schottky spectra were recorded at the 20th harmonic of the revolution frequency. As the noise power scales with the particle number, Schottky noise analysis can be used to measure the beam life time. From the spectra shown in Fig. 5 a life time of 660 s can be calculated for the stored 60 keV Co_2^- ion beam. A Gaussian fit to the spectra enables the determination of the momentum spread of the stored ion beam. Directly after injection a sigma value of $1.1 \cdot 10^{-3}$ for the momentum spread $\Delta p/p$ was found. A sensitive method for the detection of weak stored ion beams is to bunch the beam. For ion beam bunching a rf system, essentially a 35 cm long drift tube, is installed in the CSR storage ring. More details of the rf system are given elsewhere [3]. The closed orbit of the bunched ion beam can be measured with six beam position monitors (BPM), each consisting of a horizontal and verti-

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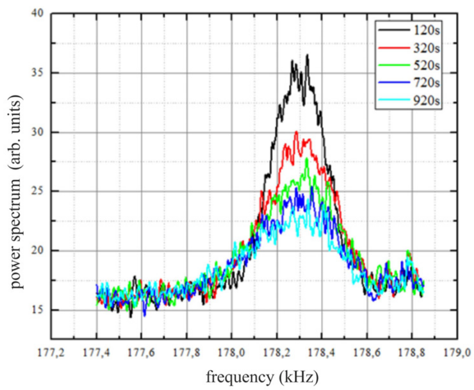

Figure 5: Measured Schottky spectra at different times after injection of a Co_2^- ions (E=60 keV). The injected ion number was about 10^8.

cal position pick-up [5]. These pick-ups are of the diagonal slotted linear pick-up type with a circular aperture. The overall beam position monitor length is approximately 29 cm and the diameter of the electrodes is 10 cm. The pick-up shielding tube is electrically isolated from the experimental vacuum chamber. Beam position measurements were made to measure the closed orbit of the stored ion beam, as well as to determine the dispersion of the storage ring at the pick-up positions. In these measurement an Ar^+ ion beam was injected into the CSR and the closed orbit was changed via variation of all electrostatic potentials by $\Delta U/U$. With $D_x = -2\frac{\Delta x}{\Delta U/U}$, where Δx is the change of the closed orbit, the dispersion at the location of the BPMs can be determined. Due to the symmetry of the storage ring, the dispersion at the six pick-up positions should be identical. The measurements yielded an average dispersion of $\overline{D}_x = 2.17$ m, where the 6 measured values for the dispersion were in the range of 2.09 m to 2.23 m. Calculations using the G4beamline code [6], where ions were tracked through the real fields of the storage ring lead to a dispersion of D_x=2.14 m, which is close to the measured value. Furthermore, one plate of the pick-up system was used to determine the horizontal and vertical tune of the storage ring when an Ar^+ 60 keV ion beam was injected with an horizontal and vertical offset to the central orbit. Due to the betatron oscillations of the whole beam, in both the horizontal and vertical direction, betatron side bands are generated in the pick-up frequency spectrum located at frequencies: $f_{x,y} = f_0(n \pm q_{x,y})$, where f_0 is the revolution frequency, n is an integer number and $q_{x,y}$ is the non-integer part of the horizontal and vertical tune. A measured pick-up spectrum of a horizontal pick-up plate is displayed in Fig. 6. The highest three peaks in the spectra belong to an integer number of the revolution frequency, whereas the small peaks marked with f_x are the betatron side bands. From this measurements a horizontal tune of $Q_x = 2.84$ can be derived, where the integer part of the tune is determined from simulations.The measured horizontal and vertical tunes were used to determine the effective lengths of the two quadrupole families by comparing the measured tunes with the calculated tunes. This comparison

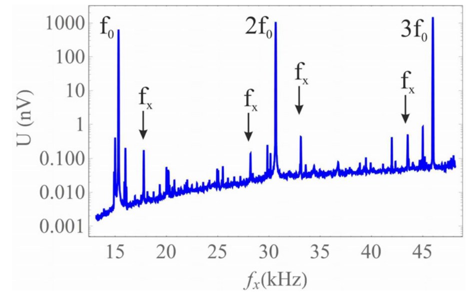

Figure 6: Spectrum of a pick-up signal induced on a horizontal plate.

leads to an effective length of 0.208 m for quadrupole family 1 and 0.209 m for family 2, respectively, which are very close to the effective length $l_{eff} = 0.212$ m obtained from finite element calculations.

CONCLUSIONS AND OUTLOOK

Beam lifetimes greater than 1000 s, as anticipated, could be reached from storing ion beams at cryogenic temperatures below 10 K. These temperatures offer an an environment of uniquely low radiation , which enables vibrational and even rotational relaxation of molecular ions during their storage in the CSR. An electron cooler for phase space cooling is currently under construction. The completion the electron cooler will allow measuring the profile of stored ion beams with the help of the dissociative recombination process between the positive single charged molecules and the free electrons of the electron cooler. The neutral fragments from this process are detected via a position sensitive detector located at the straight ahead position of the cooler. The center of mass of the neutral fragments reveals the transverse electron cooling process [7] and its distribution can be used to calculate the ion beam profile in the electron cooler. At CSR, fragment detectors based on microchannel plates were already set up and tested at cryogenic temperatures [8].

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