

CRYOGENIC ION BEAM STORAGE

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Abstract

The design of the electrostatic Cryogenic Storage Ring (CSR) currently being built in Heidelberg, Germany will be presented. The Cryogenic Trap for Fast ion beams (CTF), which was used to develop the concepts and technology required to build the CSR, has demonstrated cryogenic ion beam storage at temperatures down to 2 K for 2-8 keV cations and anions at residual gas densities equivalent to pressures on the order of 10^{-13} mbar at room temperature. Some of the recent results in storing ion beams at cryogenic temperatures will be presented, including the first betatron frequency measurement in an ion beam trap and the application of the knock-out mass selection technique.

PROJECT GOALS AND MOTIVATION

The electrostatic Cryogenic Storage Ring (CSR) will allow long storage times and phase-space cooling of ion beams with energies in the range of 20 to 300 keV per charge for highly charged atomic ions to polyatomic molecules. As the vacuum chambers will approach temperatures below 10 K, molecular ions will be radiatively cooled to their rovibrational ground states. The ability to prepare species in such rotational and vibrational quantum states will allow the expansion of the atomic and molecular physics program currently being pursued by room temperature storage rings such as the Test Storage Ring (TSR). The long ion storage times will be made possible by the optimized cryogenic pumping concepts developed and tested using the Cryogenic Trap for Fast ion beams (CTF).

The CSR will be a bakeable electrostatic cooler storage ring with a circumference of 35 m capable of operating between 2 to 300 K (see Fig. 1). Four straight sections will be dedicated to experiments and diagnostics, while the corners will use two 6° and two 39° bending electrodes allowing the injection and detection of a wide range of ionic masses and charge states. One straight section will include a unique photocathode electron cooler [1], which will allow merged beam experiments with electrons as well as the opportunity for phase space cooling with cold intense low-energy electron beams.

CSR DESIGN OVERVIEW

The vacuum chambers containing the ion beam of the CSR (see Fig. 2) will be cooled using 2 K super-fluid he-

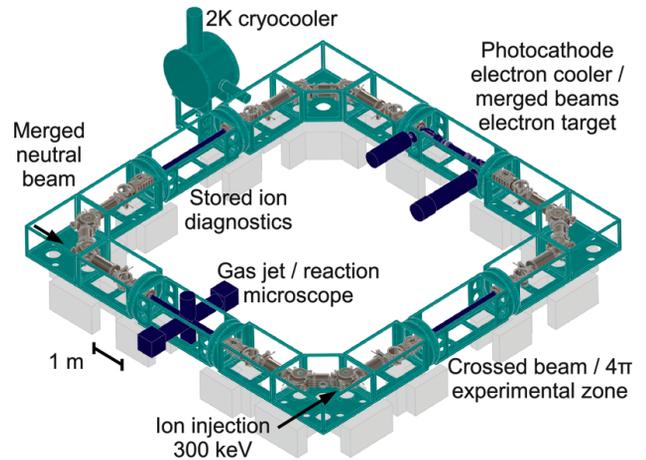


Figure 1: CSR schematic layout.

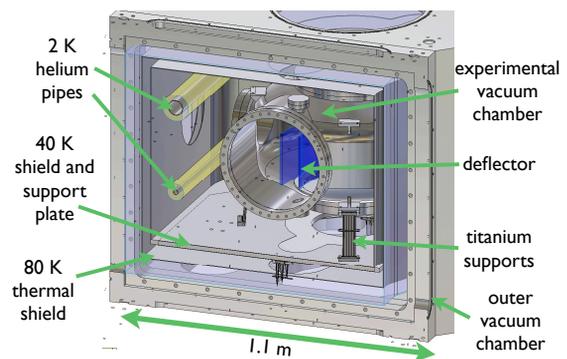


Figure 2: CSR corner chamber cross section.

lium from the cryocooler which is currently being used to cool the CTF [2]. The chambers will be enclosed in two thermal shields (at 40 K and 80 K) and multi-layer insulation, all of which will be encased in an outer vacuum chamber. Titanium supports between the inner vacuum chamber and the 40 K shield, and again from the 40 K shield to the outer vacuum chamber will support the cold chamber weight while providing the necessary thermal isolation. Precision alignment of the ion optic elements throughout the ring operational temperature is accomplished by mechanically de-coupling the electrode supports from those used for the inner vacuum chambers (see Fig. 3).

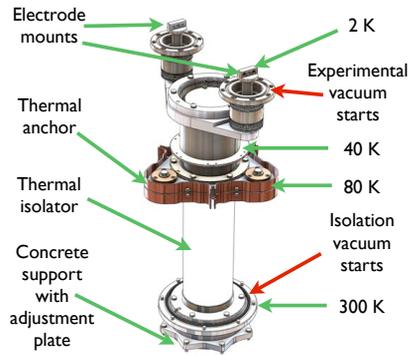


Figure 3: Precision cryogenic ion optic support.

CSR Pumping and Cooling Technique

As described below, room temperature equivalent pressures on the order of 10^{-13} mbar were achieved using cryopumping surfaces cooled to 2 K after baking the inner vacuum chambers to 600 K. The CSR will use a combination of ion getter pumps, non-evaporable getter strips, UHV bakeable cryopumps (based on the first UHV bakeable cryopump tested in the CTF), 2 K surfaces distributed along the beam path, and the cryogenic vacuum chambers themselves. The inner vacuum chambers of one corner, shown in Fig. 4, will use a copper block with direct contact to both the 2 K super-fluid helium supply line and the inner experimental vacuum to ensure adequate hydrogen pumping (cooling units, shown in red, mounted on removable flanges, in blue). Additional copper blocks connected with high purity copper to the vacuum chambers will be used to cool the chambers to temperatures below 10 K. A variation of this concept was tested in the CTF and similar temperature distributions for the CSR are expected.

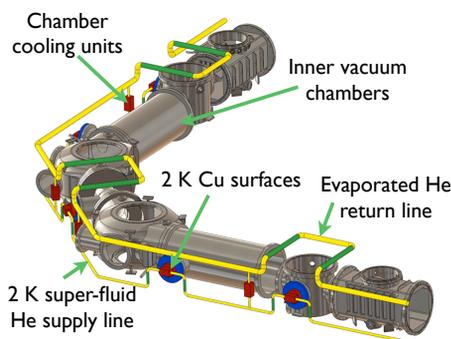


Figure 4: CSR cryogenic chambers with liquid helium pipes and 2 K pumping surfaces.

THE CRYOGENIC TRAP FOR FAST ION BEAMS (CTF)

As shown in Fig. 5, the CTF consists of a 0.8 m long electrostatic trap [3] mounted inside a 3 m long cryogenic

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vacuum chamber assembly, which is cooled by 2 K superfluid helium evaporation. This assembly is enclosed in thermal shields at 40 K and 80 K and multi-layer insulation, all of which is encased in a large outer vacuum chamber pumped to around 10^{-6} mbar. After confirming the 2 K cooling methods and measuring the temperature distribution of the various components [4], 2-8 keV ions (N^+ , N_2^+ , Al_n^- with $n=1-5$, among others) were injected using an ion optic beam line which consists of 2 einzel lenses, a "beam cleaner", a faraday cup, two sets of steerer electrodes, as well as a beam viewer [5]. The beam cleaner consists of four pairs of electrostatic plates which vertically displace the beam while it passes through a differential pumping tube, effectively acting as a chopper, blocking any neutrals coming from the source region, before guiding the beam back along the initial beam axis. The first plate can be switched, allowing the creation of a pulsed beam of a given length. Behind the CTF, a second beam viewer as well as a chevron micro-channel plate (MCP) particle detector were installed in a baked room-temperature extension to observe the neutral fragments that escape the electrostatic trap.

Measurement of Extremely High Vacuum

Neutral fragments from the stored 7.1 keV N_2^+ beam were counted with the MCP detector as a function of the time after beam injection. Ions were stored for 20 s, after which the trap was turned off and the MCP dark count rate was measured for 4 s. This procedure was repeated as the CTF was slowly warmed from its initial cryogenic state to room temperature. Electron capture is the only ion loss process leading to neutrals on the MCP, resulting in a detector rate, R , and the number of neutral particles in each injection, N_c .

$$N_c = \int_0^{\infty} R(t) dt = \text{const.} N_0 \frac{\tau}{\tau_c}, \quad (1)$$

where N_0 is the number of ions in the trap, τ is the measured exponential storage lifetime, and τ_c is the lifetime associated exclusively with losses due to electron capture. As τ_c scales with the inverse of the residual gas density, n , a reference point ($n_r = 1.25 \cdot 10^7$ /cm³, an electron capture dominated lifetime $\tau_r = 1.2$ s, $N_{c,r} = 20,000$ neutral particles per injection) in addition with constant beam intensity and trap settings yields:

$$\frac{n}{n_r} = \frac{N_c \tau_r}{N_{c,r} \tau}. \quad (2)$$

As shown in Fig. 6, comparing the reference value to the measured cryogenic lifetimes around 17.5 s with 350 neutral particles per injection yields a density on the order of $1.5 \cdot 10^4$ molecules/cm³, corresponding to a vacuum limited lifetime of around 1000 s or a room temperature pressure equivalent of $6 \cdot 10^{-13}$ mbar. Subsequent CTF improvements including the reduction of 300 K radiation along the

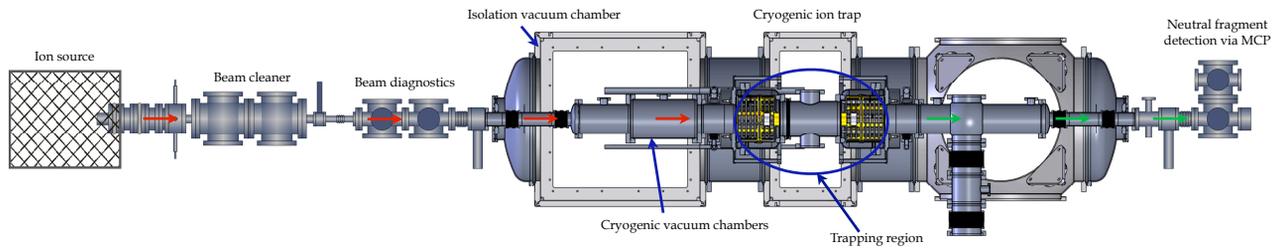


Figure 5: Cryogenic Trap for Fast ion beams (CTF) schematic (see text for more details).

beam axis, baking the cryogenic vacuum chambers, improving the stability of the trap potentials, and increasing the 2 K vacuum chamber surface area, were able to substantially increase the measured ion lifetime to over 300 s.

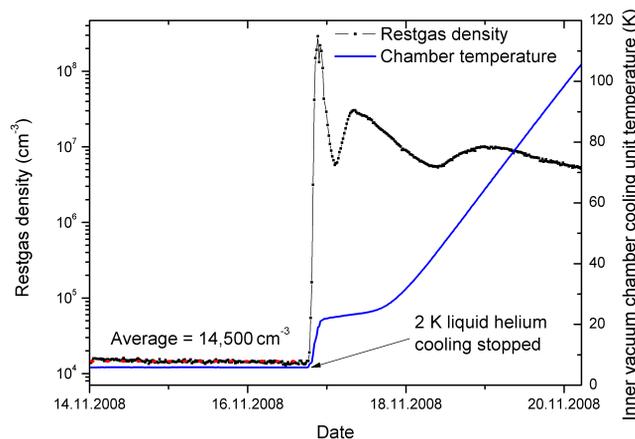


Figure 6: Restgas density and vacuum chamber temperature plotted as a function of time while warming-up from 2 K.

Transverse Tune and Knock-Out Mass Selection

Three cylindrical pickup electrodes [5] are located in the middle of the CTF's ion trap, one non-segmented electrode and two four-fold radially segmented pickup electrodes. The non-segmented pickup is primarily used to monitor the ion bunch in the trap, whereas the segmented pickups can be used for exciting and observing the transverse ion motion. By applying radio-frequency (RF) noise of a few volts with a given bandwidth to half of a segmented pickup, ions with the corresponding transverse oscillation (betatron) frequency can be selectively excited and ejected from the acceptance region of the trap (see Eq. 3). This knock-out mass selection technique, while commonly employed in storage rings, had not previously been used in electrostatic ion traps. N_2^+ with an energy of 7.1 keV was trapped and after a 1 s delay, RF noise at a given frequency was applied for 2 s. By scanning the applied noise frequency and plotting this with respect to the inverse of the observed ion bunch decay rate, the required resonant frequencies to selectively knock N_2^+ out of the trap were determined (see

Fig. 7). Maxima in the beam decay rate occurred at transverse (betatron) oscillation resonances given by the tune of the trap and the ion oscillation frequency in:

$$f(n) = f_0(n \pm q), \quad (3)$$

where $f(n)$ is the applied frequency, f_0 is the ion oscillation frequency, and n and q are the integer and non-integer part of the trap's tune, respectively.

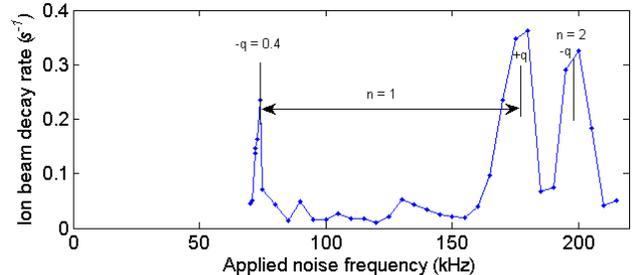


Figure 7: RF noise of a few volts used to resonantly knock-out stored 7.1 keV N_2^+ when the applied frequency fulfills the conditions in Eq. 3.

The three measured peaks allowed the determination of the trap's tune, where $q = 0.4$, for this particular set of trapping potentials, which agrees with the theoretical values from simulations [6].

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