THE DIAGNOSTICS SYSTEM AT THE CRYOGENIC STORAGE RING CSR

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Abstract

A cryogenic electrostatic storage ring (CSR) is under construction at the Max-Planck-Institut für Kernphysik Heidelberg, which will be a unique facility for low velocity phase space cooled ion beams. Among other experiments the storage and cooling of molecular ions in their rotational ground state is planned. To meet this requirement the ring must provide a vacuum with a residual gas density below 10000 molecules/cm^3, which will be achieved by cooling the vacuum chamber to 2-10 K. The projected stored beam current will be in the range of 1 nA - 1 μA. The resulting low signal strengths of the beam position pick-ups, current monitors and the Schottky monitor put strong demands on these diagnostics tools. The very low residual gas density of the CSR does not allow using a conventional residual gas monitor to measure the profile of the stored ion beam. Thus, other methods were investigated. An overview of the CSR diagnostics tools and procedures will be given.

INTRODUCTION

The CSR will be a fully electrostatic storage ring used to store atomic, molecular and cluster ion beams [1]. The beam optics consists of quadrupoles, 6° deflectors to separate the ion beam from neutral reaction products and 39° deflectors. It will be possible to merge the ion beam with neutral particles and laser beams. The experimental straight sections contain an electron cooler and a reaction microscope for reaction dynamics investigations. One linear section is uniquely reserved for diagnostics, which will contain a beam viewer for the first turn diagnosis, a Schottky pickup, a current monitor for bunched ion beams, a sensitive SQUID-based cryogenic current comparator (CCC) and two beam position monitors (BPM) (see Fig. 1).

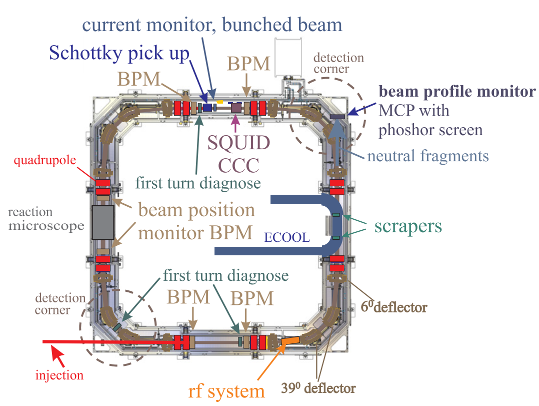

Figure 1: Overview of the CSR diagnostics system.

INTENSITY MEASUREMENT OF A BUNCHED ION BEAM

A current pick-up consisting of a tube surrounding the stored ion beam will be used to measure the total intensity of the electron cooled, bunched ion beam. If the pick-up electrode is loaded with a pre- amplifier with a very high input resistance the spectrum of the pick-up voltage $\hat{U}_n$ can be expressed by:

$$\hat{U}_n = \frac{L}{v \cdot C}\hat{I}_n, \tag{1}$$

where L describes the pick-up length and v the velocity of the ions. The total capacity from the pick-up, cable connecting the pick-up with the preamplifier and the preamplifier is denoted by C . The bunch length w of the bunched electron cooled ion beam is space charge limited, having a parabolic longitudinal density profile [2]. The current spectrum $\hat{I}_n$, at the harmonic number n of the rf frequency f_0 ($f_0 = \frac{\omega_0}{2\pi}$), of a beam having a parabolic charge line distribution is determined by the bunch length w:

$$\hat{I}_n = \frac{6 \cdot \bar{I}(\sin(nw\omega_0) - nw\omega_0\cos(nw\omega_0))}{n^3 w^3 \omega_0^3}, \tag{2}$$

The dependency of the bunch length w on the average beam current $\bar{I}$ can described by [2]:

$$w = C_0 \sqrt[3]{\frac{3(1 + 2\ln(\frac{R}{r}))\bar{I}}{2^4\pi^2 c^4 \epsilon_0 \gamma^2 n^2 \beta^4 U}} . \tag{3}$$

The bunch length w in formula (3) is determined by the beam intensity $\bar{I}$, the resonator voltage U, the number of bunches n in the ring (circumference C_0) and the beam velocity β in units of the speed of light c. The constant ϵ_0 is the absolute permittivity and γ is the relativistic mass increase (for CSR energies $\gamma = 1$). R denotes the radius of the beam tube and r is the average beam radius, defined by the $2\sigma_r$ value of the transverse beam width. From equation 1, 2 and 3 a formula can be derived which can be used to calculate the average beam intensity $\bar{I}$ from the measured voltage spectrum $\hat{U}_n$ of the pick-up signal. Since $w << 1/f_0$ equation 2 can be Taylor expanded , resulting in an approximative formula to calculate the average beam intensity $\bar{I}$ from the measured voltage spectrum amplitude $\hat{U}_1$ at rf frequency f_0:

$$\bar{I} = \frac{vC}{L}\frac{\hat{U}_1}{2} \tag{4}$$

At the TSR storage ring an experiment was carried out to determine the dependency of the component $\hat{U}_1$ of the

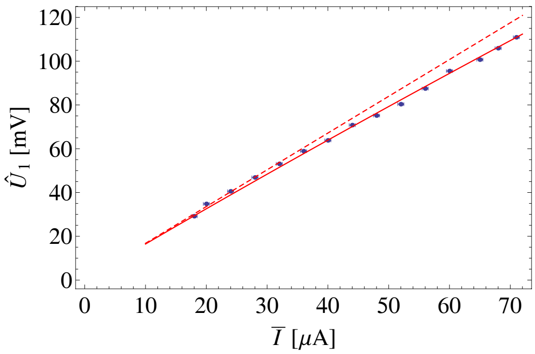

Figure 2: Measured pick-up signal as a function of the current of a silicon beam having a velocity of $\beta = 0.0872$.

pick-up voltage spectrum on the average beam current $\bar{I}$. This measurement was performed with $^{28}Si^{8+}$ ions (E= 57 MeV). The average beam current was measured with the DC transformer of the TSR storage ring. As shown in figure 2, $\hat{U}_1$ increases linearly at low ion intensities with the stored intensity as predicted by equation 4. The solid red line in figure 2 is a fit through the measurements using equation 1, 2 and 3 where the capacity C was used as a free fit parameter. From the fit a value of 171 pF could be derived for C which is close to the capacity C= 176 pF measured using an LC meter. The red dashed line is the calculated spectrum $\hat{U}_1$ using equation 4 with C=171 pF. The capacity from the fit can now be used to determine the beam current for any ion species having different ion velocities. Because the spectrum of the pick-up signal scales with the inverse of the ion velocity (compare equation 4) this method to determine the absolute intensity of an electron cooled, bunched ion beam is very sensitive for low velocity ion beams. At beam velocities of $\beta \approx 0.01$ an absolute intensity determination much below 10 nA is therefore possible.

POSITION PICKUPS

In total six beam position monitors [3], each consisting of a horizontal and vertical position pick-up, are planned to be installed in the CSR. The diagonal slit type linear pickups with a circular aperture will be used. The overall beam position monitor length will be approximately 25 cm and the diameter of the electrodes will be 10 cm. The pick-up itself is mounted in a grounded shielding chamber separating the actual signal from noise signals. The pick-up should be able to determine the position of ion beams with intensities down to 10 nA with an accuracy of 0.5 mm. The resulting low signal strengths together with the cold environment put strong demands on the amplifier electronics. We plan to use a resonant amplifier system. Using coils made from high purity copper, we expect a quality factor of approximately 1000. A prototype pick-up has been built in order to test resonant amplification using the wire method. The method principle was also tested in the MPI-K test storage ring (TSR) with a $^{12}C^{6+}$ beam. Concluding from these tests it should be possible to determine the position of a 10 nA ion beam with a precision of 0.5 mm at the CSR storage ring using a resonant amplification method.

BEAM PROFILE MEASUREMENTS

First Turn Diagnostics

For the first turn diagnostics we will use destructive low intensity beam profilers to detect the low intensity ion beam [4]. The profiler consists of a metal plate hit by the beam, producing secondary electrons. Using a grid the electrons are extracted and accelerated before they hit a MCP/phosphourous screen combination which an energy of 2 keV. The image of the beam is recorded via a CCD camera and analyzed by software. Two of this profiler have been successfully tested on the CSR prototype [5] .

Stored Ion beam

Due to the very low vacuum pressure of $p \approx 10^{-14}$ mbar expected at the CSR storage ring a conventional residual beam profile monitor is not useable to measure the profile of the stored ion beam. The beam profile of stored singly charged molecules can be determined by using the dissociative recombination process between the positive singly charged molecules and free electrons of the electron cooler. The neutral fragments from this process are detected with a position sensitive detector. The profile of the stored ion beam can be calculated from the distribution of the center of mass positions of the neutral fragments created in the DR process [6]. Due to the drift of the neutral fragments from the electron cooler to the detector, the measured beam profile is larger than the profile of the stored ion beam in the electron cooler. From the measured beam width σ_d at the detector position and the distance L between detector and the center of the cooler, the beam width σ_e at the cooler position can be calculated: $\sigma_e = \frac{\sigma_d}{\sqrt{1+L^2/\beta^2}}$, with the β-function at the center of the electron cooling section.
This method only works for singly charged ions and molecules. Highly charged ions will be used in experiments using a reaction microscope [7]. The gas jet of the reaction microscope can be used as a beam profile monitor if the diameter of the jet is set to below 0.5 mm. To measure the profile the stored ion beam will be scanned through the gas jet and the rate of ionized gas jet atoms are measured with an ion detector. The counting rate as a function of the beam position gives the beam profile. Since the gas jet horizontally directed the scan of the ion beam through the gas jet is performed by a periodic vertical local closed orbit shift, realized by the programmable function generators of the CSR steerers. With the small gas jet of the reaction microscope the beam profile can be measured only in the vertical direction. To get the horizontal profile, the measurements with the reaction microscope can be combined with scraper measurements. During the proposed scraper measurements the stored ion beam is moved to the scraper

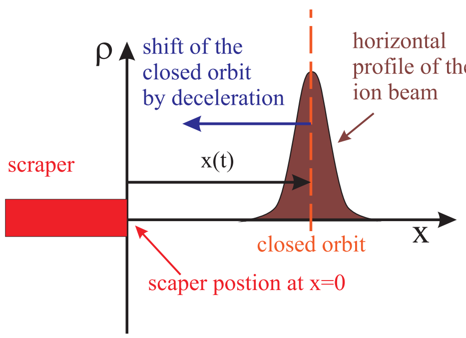

Figure 3: Principle of the profile measurements by deceleration of the ion beam towards the scraper.

position. This movement in the horizontal degree of freedom can be achieved by a local closed orbit shift or by deceleration/acceleration of the stored ion beam, if there is sufficient dispersion at the scraper location. Scraper measurements by decelerating the ion beam were realized at the S-LSR storage ring of the university of Kyoto. The principle of these scraper measurements is explained in figure 3. Deceleration was performed by applying a linear frequency shift $\alpha = \Delta f/\Delta t$ to the rf frequency f. Applying a frequency sweep changes the momentum p of the ions:

$$\Delta p = p\frac{\Delta f/f}{\eta}, \tag{5}$$

where p is the ion momentum, f is the applied rf frequency at the injection energy and η the slip factor of the storage ring, defined by $\eta = \frac{\Delta f/f}{\Delta p/p}$. A momentum change results in a shift of the closed orbit changing the distance x to the scraper position:

$$x = a_0 + D_x\frac{\Delta p}{p}. \tag{6}$$

D_x is the dispersion at the scraper position. Applying a linear frequency sweep α shifts the closed orbit:

$$x(t) = a_0 + D_x\frac{\alpha}{f\cdot\eta}t. \tag{7}$$

If $\alpha = \frac{\Delta f}{\Delta t}$ is negative the distance to the scraper position is decreased. When the closed orbit reaches the scraper position the stored ion beam is completely lost due to the betatron oscillation of the beam. The intensity starts to decrease when the ion beam touches the scraper. Assuming a Gaussian beam profile with width σ the number of ions $N(t)$ as a function of time can be calculated from:

$$N(t) = \begin{cases} N_0 e^{-t/\tau}\mathrm{Erf}(\frac{a_0+D_x\frac{\alpha}{f\eta}t}{\sqrt{2}\sigma}) & a_0 + D_x\frac{\alpha}{f\eta}t \geq 0 \\ 0 & a_0 + D_x\frac{\alpha}{f\eta}t < 0 \end{cases} \tag{8}$$

The parameter τ is the lifetime of the beam and Erf in equation 8 is the error function defined by:

$$\int_{-x}^{x}\frac{e^{-\frac{z^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma}dz = \mathrm{Erf}(\frac{x}{\sqrt{2}\sigma}). \tag{9}$$

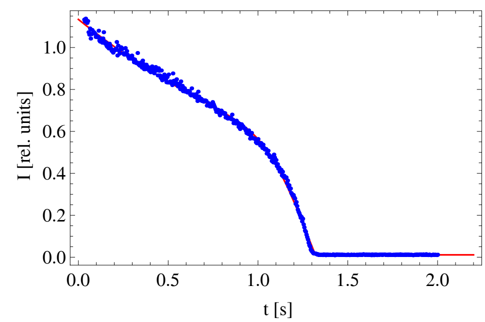

Figure 4: Intensity decrease during the scraper measurements.

Scraper test measurements were performed at S-LSR with 40 keV $^{24}Mg^{+}$ ions. In the laser cooling mode, used at this beam time, the dispersion function at the scraper position is $D_x = 1\ m$ and the slip factor of the storage ring is $\eta = 0.7$. The frequency sweep for deceleration the stored ion beam was α =-15 kHz/s. Figure 4 shows the measured intensity as a function of time (blue dots), the red line through the data points is the fit function (equation 8), where τ, σ, N_0 and a_0 are used as fitting parameters. From the fit a horizontal beam size of $\sigma = 1.6$ mm can be derived and for the center of the stored ion beam to the scraper position a distance of a_0=11.2 mm is noticeable. In the first second of the frequency sweep a decrease of the intensity visible, caused by the lifetime τ of the stored ion beam, which also was accounted for the fit routine. If a residual gas beam-profile monitor cannot be used for beam size measurements, scraping the stored ion beam by deceleration the ions to the scraper is an alternative fast method to determine the horizontal beam width. However this method can only be adopted in the horizontal degree of freedom where the dispersion function is not zero.

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