Position Pickups for 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 in Heidelberg (MPI-K), which will be a unique facility for low velocity and in many cases also phase-space cooled ion beams. Amongst other experiments the cooling and storage of molecular ions in their rotational ground state is planned. To meet this demand the ring must provide a vacuum in the XHV range (10^{-13} mbar room temperature equivalent), which will be achieved by cooling the ion beam vacuum chambers to 2 - 10 K. This also provides a very low level of blackbody radiation. The projected beam current will be in the range of 1 nA - 1 μA. The resulting low signal strengths together with the cold environment put strong demands on the amplifier electronics of the position pickups. In order to improve the precision and to push the limits of position measurement towards the nA intensity regime, we plan to make use of a resonant amplifying system, using an LC-circuit with a quality factor of $\sim$1000. A resonant amplification setup was tested in the MPI-K's Test Storage Ring (TSR). We report on signal-to-noise ratio improvements and on issues that have to be paid attention to, if resonant amplification is requested.

INTRODUCTION

The CSR will be a fully electrostatic storage ring used to store atomic, molecular and cluster ion beams [1]. The beam optics consist 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 dynamic investigations. One linear section is uniquely reserved for diagnostics which will contain a beam viewer for the first turn diagnose, a Schottky pickup, a current monitor for bunched ion beams, a sensitive SQUID based cryogenic current comparator and two beam position monitors (see Fig. 1) [2].

For the cold supply a commercially available Linde 4.5 K helium liquefier is combined with an additional connection box assuring the adaption to the CSR's helium pipe system. To reduce blackbody radiation, a maximum temperature of 10 K of the inner vacuum chamber is required. Efficient pumping of hydrogen as the main rest gas component is necessary to reach a vacuum in the XHV range which will be achieved by cooling parts of the vacuum chamber down to 2 K. For commissioning of the ring the ability of room temperature operation is required and part of the cryogenics concept is the possibility of baking out the system to at least 300 °C. The cryogenic concept leading to the ability to reach vacua in the desired range was successfully tested with the Cryogenic Trap Facility (CTF) [3].

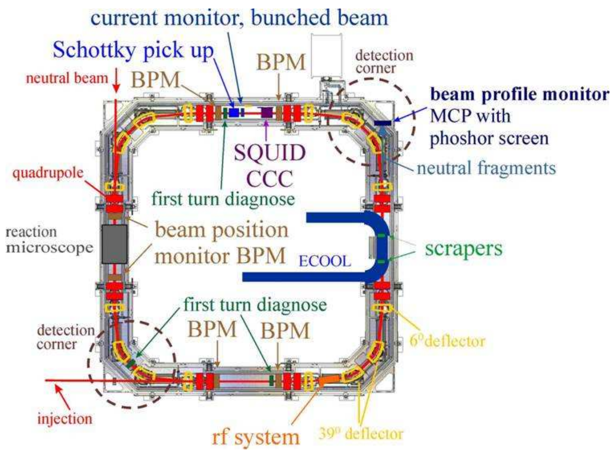

Figure 1: Overview over the CSR beam diagnostics system.

The extremely low temperatures, the large operational temperature range and the low pressures together with expected low signals are extremely challenging factors for the design of the storage ring components, particularly for the diagnostics equipment.

POSITION PICKUPS

In total six beam position monitors, each consisting of two pickups, are foreseen. One beam position monitor will be placed at each end of the diagnostics section as well as on both sides of the reaction microscope and of the third experimental section. The diagonal slit type linear pickups with a circular aperture will be used. The overall beam position monitor length will be ~ 35 cm and the apperture will be 10 cm.

Amplification Principle

Table 1 summarizes some of the relevant beam parameters. The lower current limit derives from a minimum design current to operate the ring in connection with exotic large molecules or rare short lived nuclides with a low current source and in experiments with high reaction cross sections in which it will be necessary to lower the reaction rate to prevent from detector saturation. It is requested to be able to measure the position of the center of charge of the beam to a precision of $\Delta x = 0.5$ mm. It requires a special support of the electrodes, in order to prevent the pickup from moving during cool down.

Table 1: Beam parameters

Mass range	1-200 amu
Energy range (1^+ ions)	20 - 300 keV
Frequency range	5 kHz - 200 kHz
Intensity range	1 nA - 1 μA

For amplification of pickup signals in the kHz to MHz regime, originating from bunched beams with long bunch lengths, usually high impedance amplifiers with an input DC-resistance of 1 MΩ are used. This 'conventional' - non-resonant - method is planned to be used in the CSR as well. Additionally it is planned to extend the system with the possibility of resonant amplification by means of an inductance supplementing the circuit in parallel with the combined capacity of the pickup electrodes, the signal feedthroughs and other parasitic capacities. At resonance the pickup signal is increased by the quality factor of the circuit, which is limited by losses due to the resistance of the inductance. The large range of planned frequencies is set by the extended mass range of the stored ions. A resonant system which would cover the first harmonic frequency range would have to have an extremely large and variable capacity or inductance range, which is not feasible. Therefore a system with a frequency range from 200 kHz to 400 kHz is planned, so that e.g. a beam coasting at 5 kHz had to be bunched to its 40^{th} harmonic. From the viewpoint of the coupling to the resonance circuit a narrow span of signal frequencies would allow optimal impedance matching to minimize noise transfer. In principle it is possible to bunch the beam to even higher harmonics to also move the signal frequency further away from the 1/f-noise regime. Additionally the manufacturing of the inductance for which we intend to use coils made from high purity copper became much simpler and the side effects of a high inductance coil such as self-capacity and wire resistance lowering the quality factor were of minor importance. There is, however, an upper limit for the harmonics with which the beam can be bunched, if the beam displacement is calculated from the pickup signal based on a calibration function obtained using a wire with an applied RF-frequency as a beam replacement. The EM wave generated by the wire has no component in the longitudinal direction and thus represents a TEM wave in the pickup and therefore a field of a beam with $\beta = 1$, with β being the ratio of the particle velocity and the speed of light. As described by R. E. Shafer [4], for beams with $\beta \approx 1$ the difference of the signals at the electrodes divided by the sum ($\Delta U / \sum U$), which is usually evaluated, if the beam displacement is determined, is frequency independent. There is, however, a dependence of the calibration curve on the frequency for low-β beams. Estimations using equations provided in [4] indicate that up to a harmonic number h=40 no low-β effects are expected. This number, together with the low frequency limit of a coasting beam, leads to the lower limit of the frequency range which must be covered by the resonant amplifying system. However, calculations of the low-β effects based on the finite elements method, are planned which include the special geometry of our pickup system, the result of which may shift the desired frequency range.

Signal-to-noise ratio calculations

The impedance of a non-resonant circuit with a high input resistance (1 MΩ) amplifier is determined by the impedance of the capacity ($Z \approx \frac{1}{\omega C}$). For the absolute value of the signal current I_s for bunches long compared to the length of the pickup electrode, the following equation holds [5]:

$$I_s = \omega \; I_b \; L/v. \tag{1}$$

Here I_b is the beam current, L the length of the pickup electrode (L=8 cm), v the velocity of the ions and ω the modulation frequency of the beam. If a capacity of 70 pF is assumed for the total system, a 1 nA beam coasting at $f_0 = 200$ kHz would cause a summed signal of both pickup electrodes of $\sum U = 150$ nV. Taking a reasonable scaling factor of $k = 60$ mm ($x = k \cdot \frac{\Delta U}{\Sigma U}$) the signal difference of both electrodes at $x = 0.5$ mm is just $\Delta U = 1.25$ nV, which points out the challenge of measuring the position of low current beams.

Three contributions to the total noise are considered to calculate the signal-to-noise ratio (S/N). The thermal noise $U_n = \sqrt{4 \; k \; T \; Z}$ with the Boltzmann constant k, the temperature T and the absolute value of the impedance of the amplification circuit Z. The voltage noise of the amplifier E_n, which is noise that is present independently of the source resistance. And the current noise I_n that becomes important for high source impedances as achieved in resonant circuits and contributes by $I_n \cdot Z$ to the total noise voltage. The signal is given by $I_s \cdot Z$ and thus the signal to noise ratio is given by:

$$S/N = \sqrt{\frac{I_s^2 \; Z^2}{(4 \; k \; T \; Z + I_n^2 \; Z^2 + E_n^2) \; \Delta f}}. \tag{2}$$

Δf denotes the resolution bandwidth of the signal recording system and for the following calculations it is chosen to be $\Delta f = 100$ Hz. The temperature is chosen to be $T = 4$ K. To use reasonable noise values E_n and I_n the data presented in [6] of an amplifier capable of withstanding temperatures as low as 4 K are taken. The values are $E_n = 4.7$ nV/$\sqrt{\text{Hz}}$ and $I_n = 8$ fA/$\sqrt{\text{Hz}}$ at $f = 682$ kHz. The S/N calculations are carried out for $f = 400$ kHz and since for the voltage noise a $1/f$ characteristic was found for frequencies <2 MHz the voltage noise for the calculations was corrected to $E_n = 8$ nV/$\sqrt{\text{Hz}}$. A total capacity of C=70 pF is estimated for the CSR pickup amplifier system and thus an inductance of L=2.2 mH is required. In [6] the loss resistances (R_L) of different coils wound with copper and superconducting cables with L=2.2 mH are measured. To carry out the S/N calculations with presumably achievable quality factors, from the measured values of R_L of three different coils, the quality factors for the exemplary CSR resonant system are calculated to be Q=220 with copper cable, Q=1100 with superconducting cable and Q=3300 with superconducting cable and modification of the coil shielding. The impedance in the non-resonant case at f=400 kHz is $Z_{non-resonant} = 5.6\ k\Omega$ and the impedance at resonance and thus the signal is increased by Q. Hence, for Q=3300 the impedance is $Z_{resonant}$ =18.5 MΩ. The noise contributions to the total noise are for the non-resonant case: $U_n = 11$ nV, $E_n = 80$ nV and $I_n\ Z = 0.4$ nV. For the resonant case (Q=3300): $U_n = 640$ nV, $E_n = 80$ nV and $I_n\ Z = 1,47\ \mu$V. Due to the higher impedance in the resonant case a low value of the current noise is of special interest. In the non-resonant case it is the voltage noise that contributes most to the total noise. Note at this point that in principle a better S/N ratio would be achieved if the high impedance of the resonant circuit would be transformed to the noise resistance of the amplifier $R_n = E_n/I_n$, which is in this case $R_n = 1$ MΩ. This, however, is not foreseen for the CSR resonant amplification system since the impedance transformation had to be changed for every measurement frequency and its moderate benefits do not compensate for the effort of realizing such a feature.

As an example, for a $I_b = 1$ nA beam, coasting at $f_0 = 200$ kHz with the HF set to $f_{\text{HF}} = 400$ kHz and a quality factor of Q=1100 the signal-to-noise ratio is $S/N_{\text{resonant}} = 142$ and with non-resonant amplification it is $S/N_{\text{non-resonant}} = 1$. The minimum S/N ratio needed for a precision of Δx can be calculated by $S/N_{\text{minimum}} = \frac{2\,k}{\Delta x}$. If an ideal scaling factor of $k = 50$ mm is assumed, for a precision of $\Delta x = 0.5$ mm a ratio of $S/N_{\text{minimum}} = 200$ is required. The minimum beam current for a beam coasting at $f_0 = 200$ kHz with the HF set to $f_{\text{HF}} = 400$ kHz is therefore for resonant amplification $I_{\text{resonant}} = 1.4$ nA and for non-resonant amplification $I_{\text{non-resonant}} = 0.2\ \mu$A.

Effects of coupling

For the position measurement a simultaneous measurement of the signals from both pickup electrodes is preferable. Due to the large opposing areas of the pickup electrodes, there is always a considerably large coupling capacity present. If resonant amplification of both electrodes is used, the presence of a capacity between the electrodes causes a coupling of the resonant circuits, resulting in a double resonance and a drastically reduced displacement sensitivity (Fig. 2).

To overcome this situation it is investigated to use a measurement system as depicted in Fig. 3, with which the position is measured stepwise. With relays, one electrode is short cut to ground. By this the coupling capacity simply adds up to the capacity of the active electrode which is itself connected to the resonant amplifying system. In a second step the relays are switched to the other electrode. Another benefit from this measurement is clearly that the two signals are amplified by exactly the same amplifier and

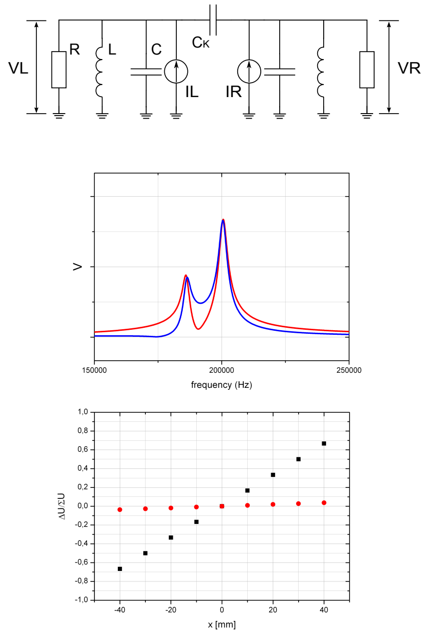

Figure 2: The effect of the coupling capacity on the resonant pickups. Top: Equivalent circuit with the capacity of the pickup electrode (+cables etc.) and the coupling capacity C_k. The difference of the signal currents *IL* and *IR* is for a diagonally slit pickup linearly dependent on the beam displacement. For beam position measurements the left and right voltages *VL* and *VR* are processed. Middle: Frequency response with the resonant circuits tuned to 200 kHz and $C = 4$ pF. The curves (red: *VR*, blue: *VL*) are calculated for a beam position of $x = 30$ mm. Bottom: Calibration curves. Black: Calibration curve for non-resonant amplification, i.e. without the inductances. The slope is decreased due to coupling with respect to the ideal case where $(VR - VL)/(VR + VL) = 1$ at $x = 50$ mm. Red: Calibration curve with resonant amplification. Its slope is decreased by a factor of 20 with respect to non-resonant amplification.

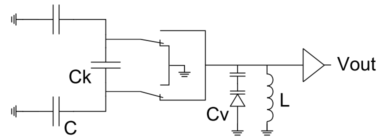

Figure 3: An amplification scheme using two relays and one tuning diode *Cv*.

essentially the same resonant circuit and thus less systematic errors may be expected that affect the measurement accuracy.

However, since the signal is proportional to the inverse of the loss resistance, $U_{\text{signal}} \propto \frac{1}{R_L}$, it is important that the losses due to the switches are the same. If a comparability of the signals of 10^{-3} is demanded, for a resonant circuit with $R_L = 20\ \Omega$ (Q=275) this requires that the resistances of the two relays must not differ by more than 0.02 Ω. If the system is realized differently such that one changer is switching from one electrode to the other and each electrode can be short cut to ground with an own switch, it is the two electrical lines in the changer which must not differ by a certain resistance in dependence on the quality factor.

For non-bunched, uncooled beams lifetimes in the order of 10^3 s are expected. If, however, the non-cooled beam is bunched, the lifetime strongly depends on the RF-noise, which will possibly decrease the lifetimes to the order of minutes. If the stepwise measurement method is used, the measured signals have to be corrected for the decreasing intensity. However, the measurement time required for $\Delta f = 100$ Hz including the time for signal acquisition, switching and rise time, which has to be considered due to high Q values, is estimated to be < 150 ms. Therefore the systematic error, that would be present in the result if a lifetime of minutes is not take into account is very low.

Test Measurement at the TSR

At the MPI-K's Test Storage Ring (TSR) the increase of S/N with the resonant method was demonstrated. For this a 50 MeV C^{6+} beam was used which had a revolution frequency of $f_0 = 509.3$ kHz. For the measurement it was decided to use a frequency of $f = 3.056$ MHz. However, when we set the RF-system to $f = 3.056$ MHz, so that six bunches are circulating in the ring, we noticed a strong crosstalk to the pickup. Therefore we decided to bunch the beam to three bunches, i.e. f_{HF}=1.528 MHz. For an non-cooled, bunched beam the ion current can be described by $I(t) \approx 2\ \overline{I}\ \cos^2(\pi\ f_{\mathrm{HF}}\ t)$, where $\overline{I}$ is the average current, and therefore the frequency spectrum has no higher harmonics. A cooled beam with short bunches was therefore used which has a strong second harmonic, which frequency is at $f = 3.056$ MHz. The advantages of this method are that there is no crosstalk from the RF-system present at the measurement frequency. However, in the CSR, position measurements with non-cooled beams are required and therefore one has to reduce crosstalk from the CSR RF system as much as possible.

The switching between the electrodes was carried out with changers as depicted in Fig. 3. An amplifier was developed which has three stages. The first stage consists of a FET cascode with a DC input impedance of 1 MΩ. At its input a capacity changing diode is used to tune the resonant circuit. The second stage is an operational amplifier that provides a fixed gain and the last stage features a variable gain amplifier. The results of the noise measurement of the amplifier are for the voltage noise $E_n \sim 3$ nV/$\sqrt{\mathrm{Hz}}$ and for the current noise $I_n \sim 150$ nV/$\sqrt{\mathrm{Hz}}$. A coil from isolated copper wire was wound with a body made from Teflon. The inductance of the coil is $L = 19.9$ μH. The quality factor of the system was determined to be Q=116. With the variable gain stage of the amplifier the signal was adjusted to the SIS3301 Flash ADC range, which has a resolution of 14 bits and a sampling rate of $f_{\mathrm{samp}} = 80$ MHz. The memory of the SIS3301 is capable of storing 128k samples, which results in a resolution of $\Delta f = 625$ Hz.

With the wire-method the scaling factor was measured to be $k = 130$ mm. Hence, for a precision of Δx <0.5 mm a signal-to-noise ratio of $S/N > 520$ is required. For a 50 MeV C^{6+} beam and a measurement frequency of $f = 3.056$ MHz one can calculate a minimum current of $I_b = 0.1$ μA for a resonant system with the decisive parameters given above. For non-resonant amplification with the same amplifier the minimum current is $I_b = 1.7$ μA if a precision of Δx <0.5 mm is required. The theoretical signal-to-noise improvement is thus 18 dB. From a number of $N = 20$ position measurements in a series during which the beam was not moved the standard deviation of a single measurement was deduced to be $s_{\mathrm{measured}} = 0.12$ mm. During the measurement the beam current was measured with a Beam Profile Monitor and found to be $I_b = 0.5$ μA. The calculated standard deviation is $s_{\mathrm{calculated}} = 0.07$ mm. The measured and calculated values are considered to be in good agreement. The calculated standard deviation of a non-resonant amplification measurement of the position is 18 dB larger, i.e. $s_{\mathrm{calculated}} = 1.2$ mm.

CONCLUSION

Calculations show that with resonant amplification it will be possible to measure the position of even nA beams to a high precision in a reasonable time, if the crosstalk of the RF system to the pickup amplifier system can be reduced significantly. The problem of coupled resonant circuits can be overcome by measuring the signal of the electrodes stepwise. Due to this in addition a lower influence of systematic errors may be expected. The drawbacks of this method are the increase of measurement time by roughly a factor of two and the fact that for low lifetimes the consecutively measured signals have in principle to be corrected for the decreasing beam intensity.

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