INTENSITY AND PROFILE MEASUREMENT FOR LOW INTENSITY ION BEAMS IN AN ELECTROSTATIC CRYOGENIC STORAGE RING

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Abstract

The cryogenic storage ring CSR is a 35 m circumference electrostatic ring, designed for molecular- and atomic physics experiments at MPI-K Heidelberg. It will operate at pressures down to 10^{-13} mbar and temperatures <10 K. The beam intensities will be in the range of 1 nA to 1 µA, particle energies with between 20 - 300 keV.

An intensity measurement for coasting beams below 1µA requires magnetic field detection devices, which are much more sensitive than existing DC beam transformers. The highest sensitivity is currently achieved using DC SQUID based cryogenic current comparators (CCCs). At GSI, a prototype of such a CCC was successfully tested in the mid 90's, reaching a resolution of ~250 pA/Hz$^{1/2}$. Recently a resolution of 40 pA/Hz$^{1/2}$ could be achieved under laboratory conditions at Jena University, however, the CCC sensitivity in an accelerator environment depends strongly on efficient shielding and mechanical decoupling.

We describe our work on adaptation and improvement of the CCC beam transformer for the CSR. Furthermore a concept for an ionisation profile monitor is discussed, which in addition to low beam intensities, has to cope with extremely low gas densities at 10^{-13} mbar.

INTRODUCTION

The CSR [1] combines a number of challenges for diagnostics development: Low currents, low ion energies, extremely low pressure, high bakeout temperatures and not least the cryogenic environment. To illustrate these boundary conditions, Table 1 shows the relevant parameters of the ring at one glance.

Table 1: Parameters of the CSR

Type	Electrostatic
Circumference	35.2 m
Corner deflectors	2x39°, 2x6°
Acceptance	100 mm mrad
Mass range	1 – 100 amu
Energy range (1^+ ions)	20 – 300 keV
Intensity range	1 nA – 1 µA
Revolution Frequency	5 - 220 kHz
Operation temperature	2 - 300 K
Bakeout temperature	< 350°C
Vacuum pressure	1×10^{-13} mbar
Mat. cold chamber	316 L
Mat. isolation chamber	Al
Outer tank cross sect.	~ 1 m^2

The mass range of A ≤ 100 in the table is at the moment considered a reasonable design value. Studies with much heavier molecules with A ≤ 2000 (at much lower intensities than 1 nA) are foreseen in a later stage of CSR operation.

In the summer 2008 the setup of the CSR prototype ion trap (Cryogenic Trap for fast ions, CTF) was completed. Numerous vacuum tests have been performed with the prototype, demonstrating a pressure in the low 10^{-13} mbar range [2], which was determined by measuring the lifetimes of stored ion beams (τ_{max} = 320 s for N_2^+). The first molecular physics experiment campaign with the CTF has been successfully completed by the time of this report. For the CSR itself, the mechanical design work for the main components has been finished. The assembly of the first ring corner will start in the fall of 2009.

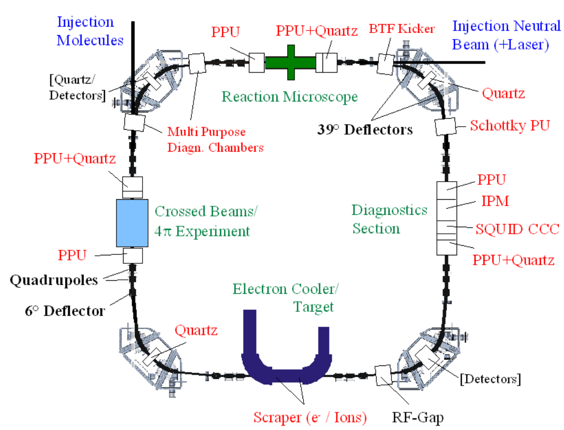

Figure 1: Layout of the CSR and diagnostics system.

The general concept for the beam diagnostics system of the CSR is shown in Figure 1. In contrast to existing or planned electrostatic rings, the CSR will have an extensive set of diagnostics devices, which is similar to the equipment of our Test Storage Ring (TSR). The four linear sections include two main experimental areas, an electron cooler/target and a section which is dedicated to beam diagnostics. Beam injection is foreseen in two corners of the ring (ions and neutral particles/laser).

For measurement of the beam intensity we have developed a mechanical and cryogenics design for a beam transformer, based on a Cryogenic Current Comparator (CCC) with a SQUID sensor, which will also be a prototype for the FAIR project at GSI.

To measure the beam profile in a non-interceptive way, we investigated the possibility of an ionisation profile monitor (IPM) at 10^{-13} mbar. At this residual gas pressure, the problem of dramatically decreasing count rates must be solved. On the other hand, increasing cross sections for charge exchange at low energies might lead to particle losses. Nonetheless we see no alternative to an IPM for the CSR.

BEAM INTENSITY MEASUREMENT

Since the first prototype of a CCC beam transformer was tested at GSI [3], the device has been steadily optimized, mainly at Jena University. On the electronics side, the bandwidth could be increased (increased slew rate) as well as the phase-locking to the periodic voltage signal from the SQUID, resulting in much higher performance and lower background noise. On the side of the pickup coil, the shielding was optimised and new materials for the toroidal core (see Fig. 2) have been investigated. The currently achieved resolution of 40 pA/Hz$^{1/2}$ under laboratory conditions [4], confirm our expectation of current measurements in the sub nA range.

The principle of the CCC beam transformer is shown in Figure 2. It basically consists of a superconducting shielding, which houses a superconducting coil on a toroidal core of high permeability. The shielding only allows the azimuthal magnetic field from the ion beam to penetrate inside, all other field components are strongly attenuated (-120 dB). If the ion beam enters the CCC, a surface current is generated due to the Meissner Effect, which is - independent from beam orientation - equal to the beam current. The shielding represents the primary winding of a transformer with the secondary winding being the pickup coil, which is again coupled to the SQUID circuit via a flux transformer for inductance matching.

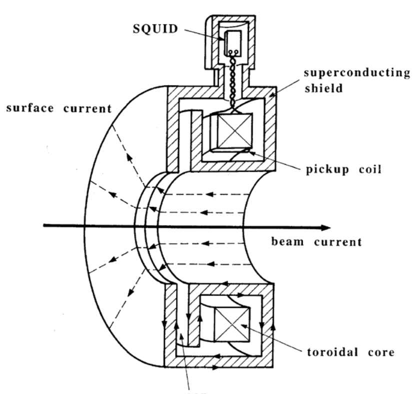

Figure 2: Principle of the CCC beam transformer [3].

For an increased performance of the system numerous ferrite materials have been tested recently in a dedicated setup at FSU Jena [6], suggesting a change from the formerly used VITROVAC® to the so called NANOPERM® material, the latter showing a high permeability over a large frequency range ($\mu_r \approx 50000$, f ≈ 1 Hz - 70 kHz), which fullfills the demand of a high inductivity pickup coil with the lowest possible number of windings (N=1). A high bandwidth is not crucial for the application in CSR, but essential for peak current measurements at FAIR.

The mechanical and cryogenic design of the CCC for CSR and FAIR takes into account that all components of the CCC have to be cooled down to liquid helium temperature, with a temperature stability of 50 mK to minimise noise and zero shift. Since the CSR also has an operation mode at room temperature, its CCC will have a separate thermal shielding, which must be closed towards the (potentially warm) beam tube and will be installed inside the inner (40 K) thermal shield (see figure 3). The SQUID and the toroidal core of the pickup coil define an upper temperature limit of only 80° C, which means the CCC shield has to be water cooled during bakeout. The liquid helium container, which houses the superconducting shielding and the attached SQUID electronics, will be suspended with wires inside the aluminum shield.

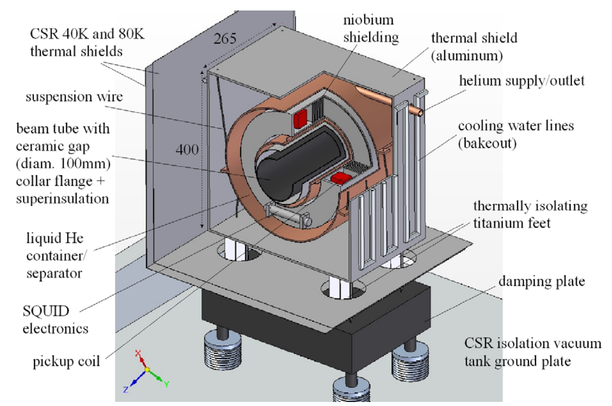

Figure 3: CCC beam transformer installation for the CSR.

Some effort is necessary for the suppression of mechanical vibrations. The shield itself is placed (with thermally isolating Ti feet) on a massive ground plate, which is - decoupled from the CSR isolation vacuum chambers by bellows - mounted on vibration damping feet on a separate support outside the isolation vacuum. Vibrations from the streaming helium in the cooling lines or from the refrigerator were measured in our prototype setup and found to be neglectable.

The CSR offers (besides a helium supply and the absence of vibration from cooling devices) the advantage of being completely non-magnetic - this concerning its optical elements as well as the used materials ($\mu_r < 0.01$). Nonetheless we are currently in the process of designing the superconducting shielding of our CCC to reach a performance, which is (despite the differing shielding geometry) identical to the shielding in the DESY setup.

BEAM PROFILE MEASUREMENT

At a vacuum pressure of 1×10^{-13} mbar, the count rate for residual gas ionisation by a 300 keV, 1 µA Proton beam is calculated with $R = \sigma\, n\, v\, \eta\, N$ to be 10 Hz. Here σ is the ionisation cross section, taken from [6], n is the residual gas density, v is the beam velocity, η is the ratio of the effective detector length to the ring circumference and N is the number of stored ions. A count rate of 10 Hz is slightly above the MCP noise level and does not allow for reasonable beam profile measurements. Therefore, the pressure must be increased to at least 10^{-11} mbar in a short, well defined section of the ring.

A number of other design criteria must be taken into account: To have proper imaging of the beam profile, high field homogeneity over a large area (beam diameter up to 8cm) is essential. At the same time, the kick on the circulating beam must be minimized. MCP operation at low temperature has been investigated in [7] and seems feasible. The IPM must be highly redundant (due to bad accessibility once installed in CSR) and have a good thermal conductivity.

To match these criteria we designed an IPM (Fig. 4), which basically consists of two identical twin IPMs with reverse polarity in x- and y-direction (kick compensation, redundancy). The MCP is screened from the extraction voltage by a grid, the whole structure is built from copper and the insulators are made from sapphire.

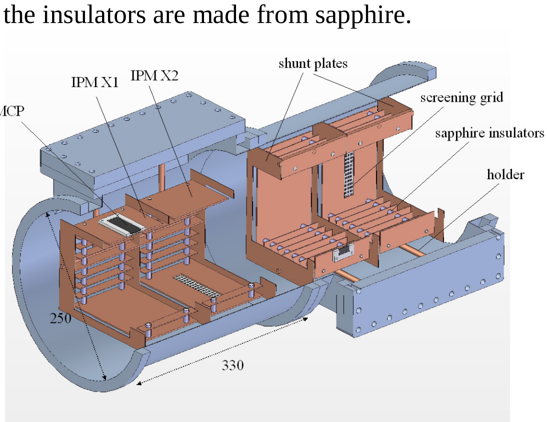

Figure 4: The IPM for CSR.

The voltages on the field shaping electrodes can be, due to the low residual gas temperature, comparatively low (100 V). On the one hand this reduces the influence of the IPM on the circulating beam, on the other hand the low IPM field can suffer from deformation caused by the MCP voltage, even if the MCP is screened with a grid. As a reasonable compromise we found an IPM voltage of $U_{El} = \pm 600$ V ($U_{MCP} = -2$ kV), which gives a resolution of $\Delta x = 45$ µm. By doing field analysis and particle tracking of a 20 keV proton beam with the TOSCA® code and then calculating the influence on the closed orbit with MAD, it turned out that at ± 600 V the closed orbit shift is 1.1 mm in the y-direction and 0.5 mm in the x-direction. The uniformity of the field is given by $E_x/E_y < 2$ % at the worst point in an area of 70 x 100 mm below the MCP. The values are acceptable and have to be seen as a worst case estimation, because the screening grid was approximated with a large mesh (3 x 3 mm) with 1mm wires due to limited available memory. Using a real 85% transmission grid, the IPM voltages as well as the closed orbit shift will be much lower.

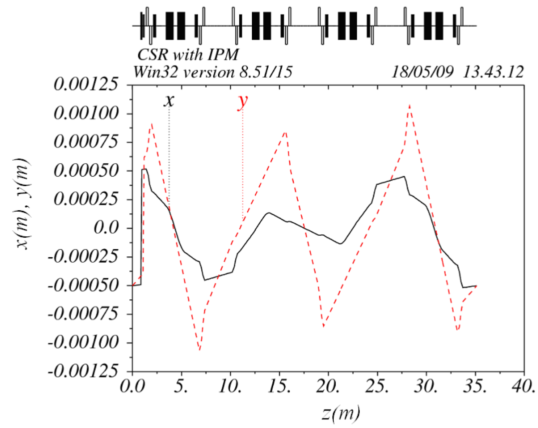

Figure 5: Closed orbit distortion of a 20 keV proton beam caused by the IPM voltage from MAD.

To increase the gas pressure in the IPM section, we are currently investigating the possibility of heating a test chamber in our CSR prototype setup. Theoretically, 10% of a monolayer of hydrogen can decrease the pressure from our present 10^{-13} mbar to 10^{-11} mbar for about 30 days, if the chamber is heated with its bakeout wires with a current of 200 mA (W ≈ 800 mW). We are considering a scheme of carefully heating the IPM chamber itself as well as neighbouring chambers, possibly in connection with a H_2 gas inlet.

OUTLOOK

After the geometry of the CCC shielding is fixed, a toroidal core with appropriate dimensions will be tested for its mechanical properties (microphony) at FSU Jena. Manufacturing of the shielding and setup of the prototype is planned until the end of 2009.

For the IPM tests in the CSR prototype, we have designed a small (5 x 5 cm) test IPM, which will be installed after the current experimental runs.

REFERENCES

[1] A. Wolf et al., “The Heidelberg CSR: Low Energy Ion-Beams in a Cryogenic Electrostatic Storage Ring”, Proc. COOL05, Galena, USA (2005), p. 473

[2] M. Froese et al., ”Cryogenic Ion Beam Storage”, Proc. PAC09, Vancouver, Canada (2009), in preparation

[3] A. Peters et al., “A Cryogenic Current Comparator for Nondestructive Beam Intensity Measurements”, Proc. EPAC94, London UK (1994), p. 290

[4] W. Vodel et al., “Current status of the SQUID based Cryogenic Current Comparator” Proc. DIPAC07, Venice, Italy (2007), p. 301

[5] R. Geithner, PhD thesis, Solid State Physics Department, FSU Jena, in preparation

[6] D.S.F Crothers, J.F. McCann, J. Phys B, At. Mol. Phys. 16 (1983), p. 3229

[7] S. Rosén et al., Rev. Sci. Instr. 78 (11), pp. 113301-113301-5 (2007)