CRYOGENIC CURRENT COMPARATOR FOR STORAGE RINGS AND ACCELERATORS

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Abstract

A Cryogenic Current Comparator (CCC) was developed for a non-destructive, highly sensitive monitoring of nA beams at the planned FAIR accelerator facility at GSI. The sensor part of the CCC was optimized for lowest possible noise-limited current resolution in combination with a high system bandwidth of about 200 kHz. It is foreseen to install the CCC inside the CRYRING, which will act as a well-suited test bench for further optimization of the CCC performance and the cryostat. In the meantime - until the completion of CRYRING - a CCC has been installed and will be tested in the antiproton storage ring (Antiproton Decelerator AD) at CERN. The pulse shape in the AD requires dedicated optimization of the sensor time response. The beam current will increase rapidly during injection from 0 to 12 µA. Since the slew rate of the overall system is limited by the CCC pickup coil, the input signal has to be low-pass filtered to not exceed the slew rate of the CCC system and to ensure a stable operation. For this purpose different low-pass configurations had been tested. In this contribution we present results of the CCC sensor for AD, CRYRING and FAIR, respectively.

INTRODUCTION

The Cryogenic Current Comparator is a well-established device in metrology for current and resistance ratio measurements [1].

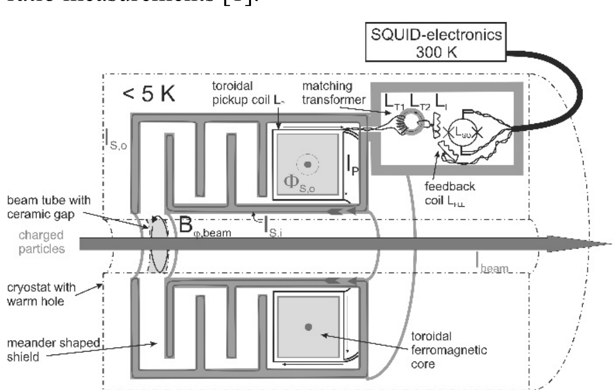

Figure 1: Schematic of the CCC.

Adapting this principle to beam diagnostics it provides a non-intercepting, absolute and precise detection of beam currents in the nA range for continuous as well as bunched beams [2].

The coupling circuit of CCC consists of a superconducting toroidal pick-up coil, a superconducting matching transformer, and a Superconducting QUantum Interference Device (SQUID) and is embedded into a meander-shaped superconducting shielding structure (see Fig. 1). The parts of the coupling circuit are connected by niobium wires and form superconducting closed loops. Due to flux conservation in such superconducting closed loops, it is possible to detect the magnetic field of constant beam currents without modulation techniques like used for DC Current Transformers (DCCT). Using state-of-the-art SQUID systems enables the detection of lowest currents in principle from DC to several MHz, but the overall bandwidth of the CCC is limited by the frequency response characteristic of the coupling circuit, which is specified by the core material embedded in the pick-up coil [3]. All these properties qualify the CCC as a suitable beam charge monitor for storage rings and accelerators.

LEAD-SHIELDED CCC AT GSI

In collaboration between GSI and University of Jena a first version of a CCC working as a beam current monitor was developed in the early 1990's [4]. In this system, the meander-shaped shield was made out of lead, whereas the coupling circuit was made out of niobium. The CCC shows very good results with a current resolution in the nA-range, but the bandwidth was limited by the SQUID-system. Also maintenance issues, like manually refilling of liquid helium prevent the usage as a standard diagnose tool. Therefore for the application in FAIR, a CCC should be developed with lower noise, higher bandwidth having cryostat with automated refilling system. As the existing CCC system at GSI provide a convenient test bench for this development, it has been re-commissioned as a prototype to test new sensor components. The SQUID and the FLL electronics were replaced by state-of-the-art devices. The re-commissioned CCC was then installed in

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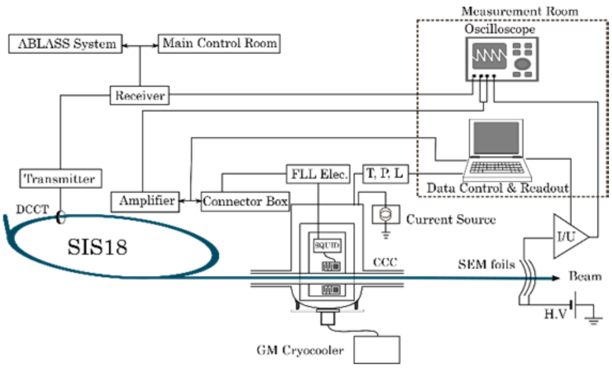

Figure 2: Schematic of measurement setup at GSI.

the extraction line of the GSI synchrotron SIS18 to monitor the extracted beam current (see Fig. 2).

In parallel to CCC measurements, a secondary electron monitor (SEM), which was installed downstream in the beam line, was used to compare the current measurements. With the help of an additional coil wound around the pickup unit, the CCC system is calibrated to a precise known current.

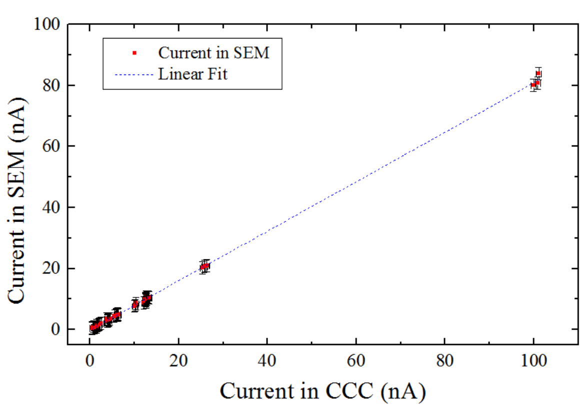

Figure 3: Comparison of beam intensity measured by SEM and CCC.

From a number of slowly extracted beam signals, the intensity measured both CCC and SEM are compared. The comparison of both signals shows a very linear relation (see Fig. 3). However, the slope is not equal to one (~ 0.8). This deviation possibly results from miscalibration of the SEM because the converting factor of the voltage output of the SEM to an equivalent beam current or a particle number strongly depends on the energy of the particles as well as the type of the element and may change with time. In turn, the CCC could also be used to calibrate the SEM.

With a current resolution of 2.3 nA (rms) corresponding to a signal-to-noise ratio of 2 at a bandwidth of 10 kHz, a number of slowly extracted beam signals were measured by CCC. A typical spill structure of a coasting beam measured by CCC and SEM are shown in Figure 4. In the figure, the spill structure is produced by 1.6×10^9 particles of Ni^{26+} extracted over 64 ms giving rise to an average current of 105.5 nA.

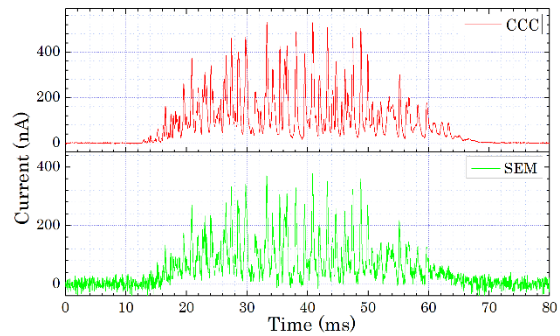

Figure 4: Comparison between SEM and CCC measurement of a 600 MeV/u beam of slowly extracted Ni^{26+} ions.

Both signals show very good temporal agreement. The measured amplitudes differ only by the factor 0.8 (see Fig. 3).

Although ideally one would expect a quasi-dc like spill structure, the beam spill structure typically contains spikes, amplitude of which exceeding several times to the average beam current. These spikes originate from the ripples associated with the power converters of magnets used for slow extraction [5]. These ripples cause over-modulations in the spill structure, i.e., the instantaneous intensity goes down to zero to very high amplitudes. For fixed target experiments (for example, hadron therapy [6]) these fluctuations are not desirable. It was shown that by bunching the beam using rf cavities in the synchrotron SIS18, these over modulation can be reduced [7].

Figure 5 shows the comparison of spill structures of a coasting beam (un-bunched beam) and a bunched beam

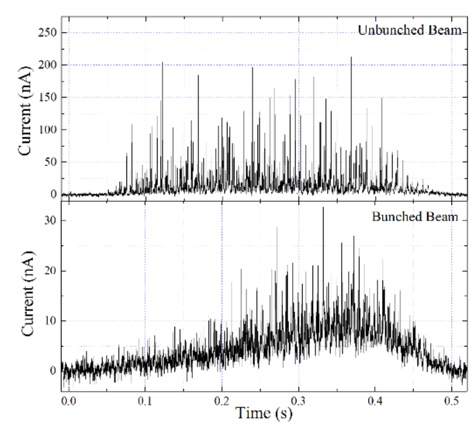

Figure 5: Comparison between the CCC measurements of a 600 MeV/u beam of slowly extracted Ni^{26+} in the unbunched case (top) and with bunching in the SIS18, before the slow unbunched resonant extraction (bottom).

The coasting beam is produced by 1.3×10^9 particles and the bunched beam is produced by 9.7×10^8 particles, both extracted over 500 ms. In the case shown, the particles are

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bunched with an rf voltage 1/7th of what used for acceleration. As shown in the figure, the bunching removes over modulation and supresses the peak amplitudes to a large extend.

IMPROVED CCC

An improved CCC was developed for the upcoming FAIR-project. A current resolution in the nA-range and a bandwidth of up to 200 kHz were achieved [3]. The CCC should be installed at CRYRING, working as a kind of test bench for FAIR but also as an experimental tool for atomic physics. At the same time, CERN's Beam Instrumentation group also had plans to install a CCC in the Antiproton Decelerator (AD), due to its unique characteristics allowing measurement of low-intensity coasting beams. A collaboration between GSI, Helmholtz Institute Jena and CERN was then put in place, where the CCC developed for FAIR-project would be first be installed in the AD until the completion of CRYRING, after the required modifications in order to adapt it to the AD beam parameters.. The main purpose of this machine is to capture the antiprotons produced by colliding a proton beam against a fixed target, decelerate them (when beam is bunched) to reduce their energy and cool down (by both stochastic and electron cooling when the beam is coasting), to create antiproton bunches suitable to be captured by low-energy anti-matter the experiments. The proposed extra low energy anti-proton facility at CERN (ELENA) will be a new ring installed downstream of the AD, with the purpose of further decelerating and cooling this antiproton beam. The most important figure of merit of these de-accelerators is the number of antiproton delivered to the experiments. Hence, a non-perturbing and absolute measurement of the beam intensity is essential to monitor any efficiency losses during the deceleration and cooling phases. At the same time there is the requirement for having a stable, automated and high-availability system which can work with almost no intervention from an expert operator. Also, the cooling of the different superconducting components should be provided by a stand-alone system, such as a cryo-cooler which should enable a closed cycle cryogenic operation, without the need for manually periodic refills of liquid helium. A special cryostat with an automated helium re-condensation unit was developed. The CCC should meet the following performance specifications: a current resolution smaller than 10 nA, a dynamic range covering currents between 100 nA and 12 µA, and a bandwidth from DC to ~1 kHz [8]. In previous measurements in laboratory environment the resolution and the dynamic range (for slow beams) was demonstrated but instabilities appear when the slew rate of the beam signal exceeds the maximum slew rate of the CCC-system. This means that for signals with higher slew rates, unwanted flux jumps occur and the SQUID electronics in the FLL-mode adjusts to different working point. If this occurs at a single point the absolute measurement offset is lost, and if this occurs continuously the complete measurement is meaningless.

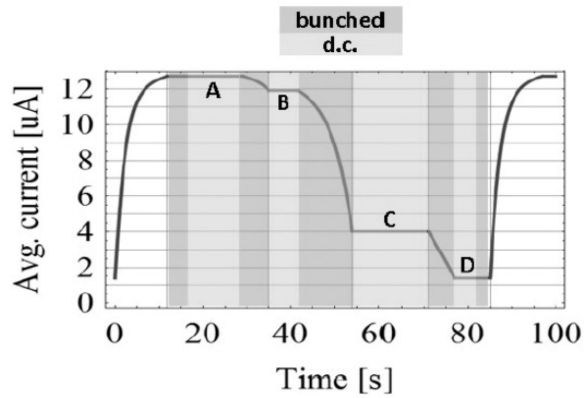

Figure 6: Expected average beam current in AD during injection and deceleration of antiprotons.

Figure 6 shows the high dynamic range of the expected beam current signal, particularly during injection where the current suddenly jumps from 0 to ~12 µA. Using the designed CCC for FAIR without any modification would impose a flux slew-rate on the SQUID of 400 MΦ_0/s, while modern SQUID/FLL systems can handle at most 1 MΦ_0/s to 5 MΦ_0/s.

This difference of two orders of magnitude can be reduced by decreasing the magnetic flux coupling into the SQUID, or by low-pass filtering the magnetic flux signal before it reaches the SQUID input. The latter solution is possible to be implemented due to the low bandwidth specification for the monitor and it is also preferable since it does not entail a loss of current sensitivity. In the AD and ELENA CCC plus cryostat systems, the signal slew-rate will be reduced by a combination of filtering in the CCC coupling circuit, and in the structure of the cryostat developed at CERN.

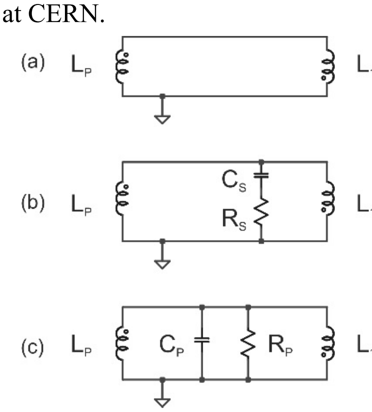

Figure 7: Connection scheme of the tested filter setup ((b) serial connection of R_S and C_S, (c) parallel connection of R_P and C_P) in the coupling circuit between the pick-up coil L_P and the primary coil L_1 of the matching transformer while (a) is the original configuration.

A low pass filter was inserted between the pick-up coil and the primary coil of the matching transformer in consequence of these requirements. Figure 7 shows the different tested setups. The first setup was a serial

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connection of a 1 Ω resistor R_S and a 10 µF capacitance C_S. The bandwidth was reduced to 7 kHz with an additional noise contribution around the resonant peak (see Fig. 8 (b)). That's why a parallel connection of a 0.225 Ω resistor R_P and a 10 µF capacitance C_P was tested. Here, the bandwidth was reduced to 1 kHz with the additional noise contribution evenly distributed from DC to the 1 kHz cut-off frequency (see Fig.8 (c)).

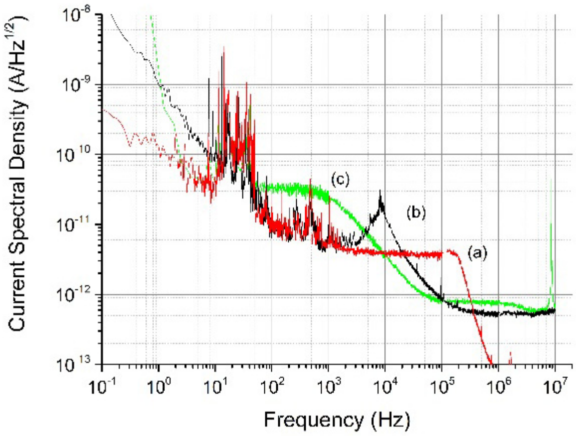

Figure 8: Current noise of the CCC in the original configuration without filtering in the coupling circuit (a), with serial connection of R_S and C_S (b), and with parallel connection of R_P and C_P.

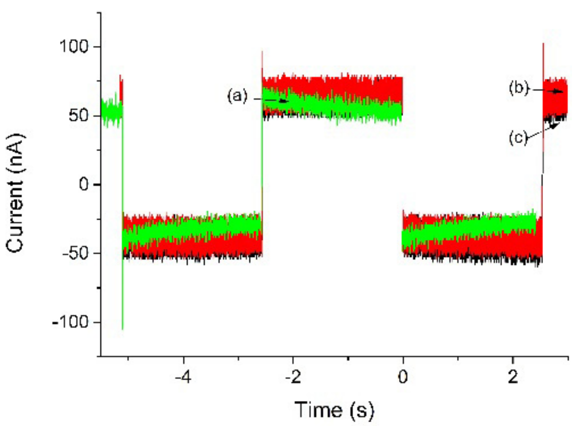

Figure 9: Step function response to a test current of 90 nA with the original configuration without filtering (a) as well as with filtering in parallel connection, applying the test current to beam simulating wire (b) or to the calibration coil (c).

This could also be seen in the step function response in Fig. 9. The test current suddenly increases by 90 nA. Two different methods were used to apply a test current. The test current can be applied by a beam simulating wire along the beam axis or by an additional wire wound around the pick-up coil. In the original configuration without filtering (see Fig 9 (a)), overshooting and a slide creeping occurs. With filtering in the parallel configuration (see Fig. 9 (b) and (c)) some overshooting is visible, too, but the signal is much more stable. In these measurements the SQUID system bandwidth of 12.6 MHz is much higher than the required 1 kHz of the complete detector. This means that the increased noise of the CCC-system could be decreased by filtering the output signal again. Another important feature, regarding measurement accuracy and calibration is also shown in Fig. 9. There is no difference to see if the beam simulation signal is applied to the beam simulating wire (b) or to the calibration coil (c). The comparison between current sensitivity of the CCC depending on whether the test signal is applied to beam simulating wire or to calibration coil is shown in Fig. 10. Both methods show a very linear behaviour in the tested dynamic range from 20 nA to 10 µA. The current sensitivity of the coupling circuit of 96 nA/Φ_0 does not differ in the limits of measurement. That means, that there is an ideal coupling of the beam's azimuthal magnetic field to the pick-up coil without any losses, giving the opportunity of an absolute, linear calibration.

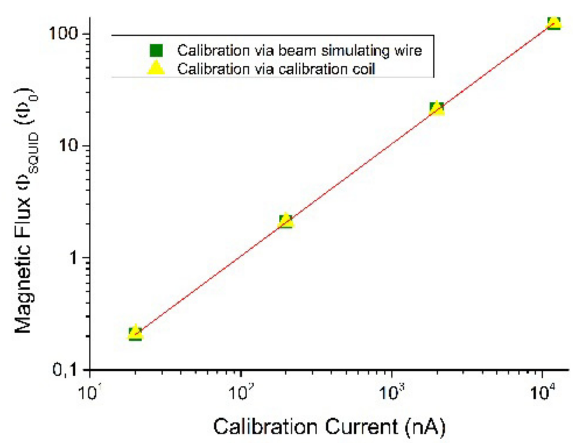

Figure 10: Comparison between current sensitivity of the CCC with test signal applied to beam simulating wire or to calibration coil.

CONCLUSION AND OUTLOOK

The CCC has demonstrated its outstanding performance in the beam line at GSI. Spill structures of extracted beams could be measured with very high temporal (0.1 ms) and current resolution (2.3 nA (rms)). The CCC could also be used for calibration of different devices like SEM, due to its own linear working function which is independent of particle energies. Using improved core materials the current noise could be reduced while the bandwidth of the overall system could be increased. If the bandwidth is not crucial, the detector could be applied to the demands of the signal. For AD the slew rate of the signal (400 MΦ_0/s) would exceed the slew rate of the CCC (< 5 MΦ_0/s). Using low pass filters in the coupling circuit could solve these problems. The CCC is delivered to CERN and installed in AD is a cryostat designed and

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fabricated by CERN with a stand-alone helium re-liquefier system and connected to the control system. Details of the AD installation and first results of beam measurements were presented by in these proceedings [9]. In the meantime the installation of the CCC at CRYRING will be prepared using the results from AD installation.

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