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BEAM INTENSITY MONITORING WITH NANOAMPERE RESOLUTION – THE CRYOGENIC CURRENT COMPARATOR (CCC)*

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Abstract

The storage of low current beams as well as the long extraction times from the synchrotrons at FAIR require non-destructive beam intensity monitoring with a current resolution of nanoampere. To fulfill this requirement, the concept of the Cryogenic Current Comparator (CCC) based on the low temperature SQUID is used to obtain an extremely sensitive beam current transformer. During the last years CCCs have been installed to do measurements of the spill structure in the extraction line of GSI SIS18 and for current monitoring in the CERN Antiproton Decelerator ring. From these experiences lessons can be learned to facilitate further development. The goal of the ongoing research is to improve the robustness of the CCC towards external influences, such as vibrations, stray fields and He-pressure variations, as well as to develop a cost-efficient concept for the superconducting shield and the cryostat.

INTRODUCTION

In modern accelerator facilities there are many applications, from rare isotopes and antiprotons in storage rings to slow extracted beams for nuclear physics experiments, which require absolute and non-destructive monitoring of ion beams with intensities down to nanoamperes. This need cannot be addressed by standard current diagnostics. Typical AC and DC current transformers are limited to intensities above microamperes. More sensitive devices like Faraday cups or secondary electron monitors (SEM) are at least partially destructive, which limits their application in storage rings, and – in case of the SEM – require elaborate calibration to compensate for aging effects. Although Schottky monitors can provide some current information, they are often not able to reach the desired accuracy at low currents and special care must be taken to calibrate them correctly, especially for their use across large frequency ranges [1].

With the high magnetic sensitivity of a SQUID sensor (Superconducting Quantum Interference Device) the cryogenic current comparator (CCC) expands the detection threshold of the traditional current transformers and can provide absolute, non-destructive current measurements independent of particle species. In the most recent installation at the Antiproton Decelerator (AD) at CERN the CCC has shown a current resolution of 5.8 nA [1] and is actively used as part of the accelerator control system during the commissioning and routine operation. In a clean lab environment, currents down to 1.3 nA with a current noise lower than 3 – 30 pA/√Hz (7 Hz – 100 kHz) can be measured [2]. Furthermore, bandwidths of up to 200 kHz with a slew rate of 0.16 μA/μs are possible [2].

With our work, we aim to further increase the current resolution by improving the stability against electromagnetic and mechanical perturbations. A custom beamline cryostat is designed to minimize interferences as well as to expand the usability by adding a self-sufficient liquid helium cooling cycle. Ultimately, we plan to install a CCC in the storage rings (CRYRING and Collector Ring) and transfer lines of FAIR in order to supply low intensity current data to both the machine experts and users, and thus have a tool to better understand the processes during slow extraction from synchrotrons as well as the physics of low intensity experiments.

In this contribution, we look at the history of the CCC to show possible applications and the problems that we encountered, followed by the latest research to address these challenges. This includes studies toward alternative (coreless) shielding geometries and superconducting materials, as well as the analysis of mechanical resonances of the housing cryostat.

HISTORIC DEVELOPMENTS

The CCC was developed in national standards laboratories to compare extremely small electric currents. One of the first who used the emerging SQUID sensors for current measurements was I.K. Harvey in 1972 [3]: see

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Table 1: Historic development of the Cryogenic Current Comparator

Institute	**Date**	**Reference**	**Comment**
NSL/NMI, Australia	1972	I. K. Harvey [3]	One of the first CCCs for current measurements.
PTB, Germany	1977	K. Grohmann *et al.* [4,5]	Shield design and first tests with an e^- beam.
Fermilab, USA	1985	M. Kuchnir *et al.* [6]	Proposal to install a CCC in the Antiproton Accumulator at Fermilab.
GSI & HIJ, Germany (GSI-Pb-CCC)	1996	A. Peters, H. Reeg, W. Vodel *et al.* [7]	Installation in the extraction line of the heavy ion synchrotron SIS18 at GSI.
INS, Japan	1998	T. Tanabe *et al.* [8]	Installation in the storage ring TARN II at KEK.
NPL, UK	2001	L. Hao *et al.* [9]	Test of HTC SQUID and shielding (in liquid N_2).
RIKEN, Japan	2004	T. Watanabe *et al.* [10]	Test of HTC SQUID and shielding (w. pulse tube).
DESY/HOBICAT, Germany	2010	R. Geithner, R. Neubert, W. Vodel *et al.* [11]	Dark current measurements of SC cavities for the TESLA linear accelerator and the EU-XFEL.
GSI & HIJ, Germany	2014	R. Geithner, F. Kurian *et al.* [12, 13]	Study of materials for flux concentrator (HIJ) and measurement of SIS18 slow extraction (GSI).
CERN, Switzerland (CERN-Nb-CCC)	2016	M. Fernandes, J. Tan *et al.* [1, 14]	Current monitor for the Antiproton Decelerator with a closed refrigeration system.
FAIR, Germany (GSI-Nb-CCC-XD, others in development)	exp. 2019	CCC collaboration [2, 15, 16, 17, 18]	Tests of the FAIR prototype, verification of shielding geometry with numeric simulations and efforts toward alternative (coreless) designs.

Table 1 for an overview of the developments. Soon after, in 1977, the German national standards laboratory (PTB) saw the potential of this method to measure the electron beam current of 100 nA generated by their Van de Graaff accelerator at an energy of 2.5 MeV [4]. For practical applications, the shielding of external magnetic fields became an important aspect, which was studied at the theoretical level by K. Grohmann et al. [5]. This work lead to the ring topology, which is still used for diagnostics of charged particle beams. In modern systems with this design typical attenuations of 135 dB are achievable [18].

M. Kuchnir et al. were one of the first to propose the installation of a CCC in an accelerator facility for the purpose of monitoring the beam intensity in the Antiproton Accumulator at Fermilab [6]. They manufactured several prototypes and adapted the design of K. Grohmann et al. using sheets of lead to construct the superconducting shield. The first application of a CCC to measure a hadron beam, however, was implemented at the extraction line of SIS18 at GSI by A. Peters et al. in 1996 [7]. They measured the spill structure of a beam of $^{20}\mathrm{Ne}^{10+}$ with an energy of 300 MeV/u and with an average current of 12 nA and achieved a resolution of 0.1 – 0.3 nA/√Hz, depending on the selected frequency range. Soon afterwards, in 1998, T. Tanabe et al. achieved a similar current resolution of 1 nA with a bandwidth of 10 Hz at the storage ring TARN II [8], which improved the accuracy of atomic cross sections measurements.

It is important to note, that these groups had to deal with a strong baseline drift of the SQUID signal following the cool down. After several days at liquid helium temperature, the drift gradually decreases and in modern installations it is confined to variations below 0.3 nA/s (25 nA per cycle of 85 s) and is linear over many seconds [1]. However, it has been shown that it is possible to compensate for these drifts to achieve absolute measurements throughout several minutes [1]. Our assumption is that the magnetic domains in the flux-concentrating core needs some time, which is longer at low temperatures, to reach an equilibrium state and the change of its magnetic permeability during this time is the reason for this baseline drift.

Once high-temperature superconductors (HTC) became accessible, in the early 2000s, L. Hao et al. at the National Physical Laboratory in the UK [9] and T. Watanabe et al. at RIKEN, Japan [10] used HTC-SQUIDS to implement CCCs that were cooled with either liquid nitrogen or a pulse-tube cooler, respectively. In general, they were less sensitive than their low-temperature counterparts and were operated with beam currents down to several microamperes.

MODERN INSTALLATIONS

In 2010, R. Geithner et al. adapted the CCC to perform dark current measurements on a superconducting cavity for the TESLA linear collider [11]. The dark current of 5 nA could be measured successfully with a noise limited current resolution of 0.2 – 50 nA/√Hz (determined between 5 and 500 Hz). Especially in this setup, it became apparent that the mechanical and acoustic vibrations raise the current noise significantly so that their suppression became an important factor in the development.

In 2011, a detailed investigation to decrease the noise contribution of the flux-concentrating core was performed by R. Geithner et al. [12] and modern SQUID electronics was installed. In combination with a higher shielding factor against magnetic perturbations, this resulted, in 2014, in a current resolution of 3.5 – 35 pA/√Hz under ideal conditions, depending on the selected frequencies

(7 Hz – 10 kHz) [13]. This CCC system was later adapted to cope with the beam at the Antiproton Decelerator (AD) at CERN, where it is installed now [1]. In addition, the CCC prototype at GSI has been updated with new electronics in 2013 and the spill structure of the slow extraction from the SIS18 synchrotron at GSI could be measured. Ultimately, these measurements lead to an improvement of the spill quality. However, with increasing sensitivity, the thermal variations caused by pressure fluctuations of the liquid helium start to become significant and compromise the current signal. In the latest setup this drift was 15 nA/mK [15].

Since it was known that mechanical perturbations can pose a problem, the CCC cryostat at the AD at CERN was designed (leading up to 2016) with an emphasis to keep the mechanical eigenmodes off critical frequency values (e.g. 50 Hz) [14]. In addition, while previous CCCs had to be filled with liquid helium manually before each measurement campaign, a closed refrigeration system was implemented. Moreover, the CERN-Nb-CCC is fully incorporated into the accelerator control system. When the beam is injected into the AD the beam of antiprotons is bunched and the slew rate of the magnetic flux can reach 93.5 $G\phi_0$/s. This is significantly higher than what the SQUID can track. As a result, at injection instead of following the current, the zero offset of the SQUID changes sharply. Nevertheless, this flux jump can be corrected with adequate calibration after each cycle. In the working configuration, a stable current resolution of 5.8 nA is achieved [1].

NEW CCC GENERATION FOR FAIR

By learning from past applications, we aim to design a cryostat that incorporates a closed refrigeration system and that is robust against mechanical perturbations. However, the cryostat should still offer the flexibility to easily mount and exchange different components of the CCC. With this CCC test bench, which is planned to be installed at the storage ring CRYRING, we will be able to test new shielding geometries and materials in an accelerator environment. Currently, the detailed mechanical design of the cryostat is done iteratively with an analysis of the resonant frequencies, with the objective of reducing the effect of mechanical perturbations.

Furthermore, simulations have shown that there is a possibility to adapt the CCC shielding geometry in a way which significantly reduces the production effort [17, 18]. The application of superconductive coatings might further reduce the material cost. Other ideas, like using two SQUID sensors in a gradiometer setup to filter out global mechanic oscillations and the use of an active damping system are explored.

Moreover, advances in SQUID technology give us the opportunity to remove the flux-concentrating core. The magnetic fluctuations of the core are the dominating intrinsic noise source and many external perturbations are amplified by the core itself, therefore, efforts to eliminate this noise are very promising [18]. A new challenge that has to be addressed before an installation at FAIR, is the radiation environment and the accumulation of a non-negligible radiation dose during an operation through many years. Therefore, the deployed Magnicon® and Supracon® SQUID sensors will be tested up to a total dose of 700 Gray at the CHARM irradiation facility at CERN.

SUMMARY AND OUTLOOK

Cryogenic current comparators have been used actively in accelerator facilities around the world to measure nanoampere currents of ion beams and expand the detection threshold of standard diagnostics. The performance of the ring-shaped magnetic shielding is well documented [5, 16, 17]. The flux-concentrating core is a major source of noise and there are promising efforts to remove it relying on modern SQUID technology [18]. It has been shown at the AD that the effect of magnet ramps, pulse tube coolers and pressure variations (periodic or well defined perturbations) can be filtered during data processing to obtain meaningful current readings for many seconds [1]. Mechanical vibrations are a source of noise and a careful design and an analysis of the mechanical eigenmodes of the cryostat are needed to avoid interference with the measurements [14]. New concepts for the CCC at FAIR will be tested in CRYRING in 2019.

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