OPTIMIZED CRYOGENIC CURRENT COMPARATOR FOR CERN'S LOW-ENERGY ANTIPROTON FACILITIES

M. Fernandes*, The University of Liverpool, U.K. & CERN, Geneva, Switzerland
A. Lees, D. Alves, T. Koettig, E. Oponowicz, J. Tan, CERN, Geneva, Switzerland
C. Welsch, Cockcroft Institute & The University of Liverpool, U.K
R. Geithner, R. Neubert, T. Stöhlker, Friedrich-Schiller-Universität & Helmholtz Institute Jena, Jena, Germany
M. Schwickert, GSI, Darmstadt, Germany

Abstract

Non-perturbative measurement of low-intensity charged particle beams is particularly challenging for beam diagnostics due to the low amplitude of the induced electromagnetic fields. In the low-energy Antiproton Decelerator (AD) and the future Extra Low ENergy Antiproton (ELENA) rings at CERN, an absolute measurement of the beam intensity is essential to monitor operational efficiency and provide important calibration data for all AD experiments. Cryogenic Current Comparators (CCC) based on Superconducting QUantum Interference Device (SQUID) have in the past been used for the measurement of beams in the nA range, showing a very good current resolution. However these were unable to provide a measurement of short bunched beams, due to the slew-rate limitation of SQUID devices and their strong susceptibility to external perturbations. Here, we present the measurements and results obtained during 2016 with a CCC system developed for the Antiproton Decelerator, which has been optimized to overcome these earlier limitations in terms of current resolution, system stability, the ability to cope with short bunched beams, and immunity to mechanical vibrations.

CURRENT MEASUREMENT OF LOW-INTENSITY BEAMS

Low-intensity charged particle beams present a considerable challenge for existing beam current diagnostic devices. This is particularly true for beams with average currents below 1 μA which is the resolution limit of standard DC Current Transformers [1]. Other monitors, such as AC Current Transformers or Schottky monitors are able to measure low-intensity beam currents, but neither can simultaneously provide an absolute measurement, with a high current and time resolution, which at the same time is independent of the beam profile, trajectory and energy.

At CERN's low-energy antiproton ($\bar{p}$) decelerators, the AD and ELENA (currently under construction) rings, both bunched and coasting beams of antiprotons circulate with average currents ranging from 300 nA to 12 μA. The AD cycle consists of alternate phases of deceleration, where the beam is bunched, and beam cooling, when the beam is debunched and its velocity is kept constant. The beam is also bunched at injection and extraction. The AD current profile during the whole deceleration and cooling cycle along with the maximum slew-rate during phases where the beam is bunched is shown in Fig 1. The $\bar{p}$'s are injected in the AD with a momentum of 3.5 GeV corresponding to $\beta = 0.967$, and are extracted with 100 MeV and $\beta = 0.106$.

Having a current measurement able to cope with these characteristics would greatly help the optimisation of the machine operation. To meet these requirements, a low-temperature SQUID-based Cryogenic Current Comparator (CCC) system is currently under development [2]. Similar devices have already been developed for electrical metrology [3], and have already been used for beam current measurements in particle accelerator [4]. The current project, is a collaboration between CERN, GSI, Jena University and Helmholtz Institute Jena to develop this technique further.

The main design specifications for the monitor are: beam current resolution < 10 nA; and a measurement bandwidth of 1 kHz.

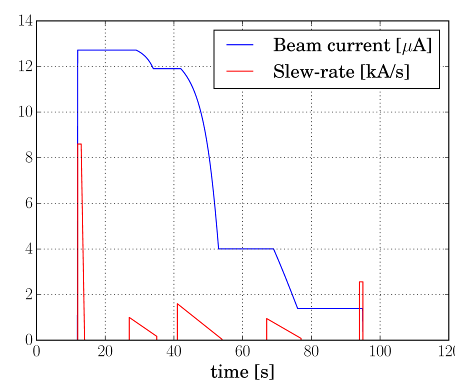

Figure 1: Nominal beam current during an AD cycle, and maximum beam current slew-rate in bunched beam phases.

OVERVIEW OF THE FUNCTIONING PRINCIPLE OF THE CCC

The CCC (see schematic in Fig. 2) works by measuring the magnetic field induced by a charged particle beam. This field is concentrated in a high-permeability ferromagnetic pickup core, from which it is coupled into the SQUID sensor via a superconducting flux transformer. The SQUID's are highly sensitive magnetic flux sensors that permit the measurement of the weak fields created by the beam. The superconducting magnetic shield structure around the pickup-core

* e-mail: miguel.fernandes@cern.ch

ISBN 978-3-95450-177-9

renders the coupled magnetic field nearly independent of the beam position and also shields the system against external magnetic field perturbations [5]. The feedback loop in the SQUID read-out implements a so called Flux Locked Loop (FLL) [6], increasing the dynamic range of the SQUID, but imposing a stability limit on the maximum slew-rate of the input signals.

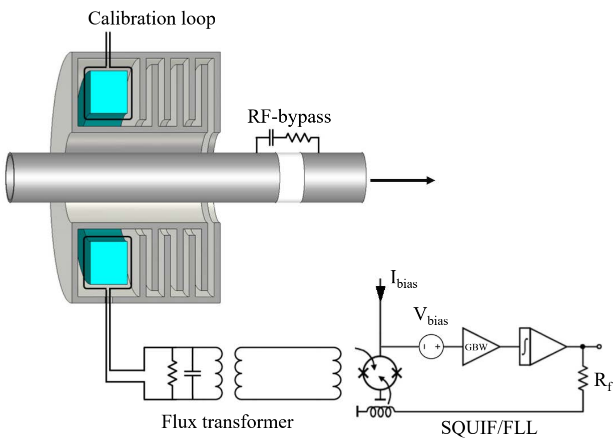

Figure 2: Schematic of the CCC.

The unique advantage of the CCC monitor is its ability to measure the average current of both coasting and bunched beams with nA resolution. Previous installations of the CCC for beam current measurements were, however, usually restricted to slowly extracted beams in transfer lines. When measuring bunched beams, the high slew-rate soon becomes a limiting factor [7] as is the case in the AD (see Fig 1). In order to reduce the slew-rate of the signal coupled to the SQUID, a filter has been implemented in the coupling circuit [8]. The CCC is also very sensitive to mechanical and electromagnetic interference, which represent an additional limitation when operating in an accelerator environment.

CRYOSTAT DESIGN

To house the CCC monitor a LHe-bath cryostat fed by a pulse-tube reliquefier was designed and manufactured. As shown in Fig. 3 the cryostat is composed of three main parts: helium vessel (HV), thermal radiation shield (TS) and vacuum vessel (VV). The VV beam tube has a diameter of 103 mm, leaving enough space to fit the inner walls of the TS and HV beam tubes between the VV beam tube and the 185 mm inner diameter of the CCC monitor. To prevent the mirror currents induced by the AD beam from shielding the beam's magnetic field from the CCC, electrically insulating ceramic isolators are integrated into the inner walls of the HV and VV with a 4 mm gap integrated into the TS beams tube. The SQUID cables are routed to their data acquisition equipment through a dedicated feedthrough on the HV.

The main design challenge was to optimize the thermal and mechanical performance of the cryostat to retain a stable amount of liquid helium while minimizing the transmission of vibrations to the CCC. The masses of the HV (145 kg including 55 kg for the CCC) and TS (55 kg) are supported using independent sets of twelve titanium support rods which are dimensioned to increase the resonant frequencies of the HV and TS above 50 Hz. Titanium was used due to its low stiffness to thermal conductivity ratio. To isolate the CCC from vibrations an external Cryomech® PT415 helium reliquefier was used and connected to the cryostat using a flexible bayonet connection (BC) designed to mechanically isolate the two systems. To isolate the 850 kg cryostat assembly from ground vibration it is mounted on a 955 kg concrete mass and four Apsopur® anti-vibration mats a configuration which is calculated to isolate 92 % of vibrations at 50 Hz. A detailed description of the cryostat design and first performance measurements obtained during the 2015 run can be found in [9].

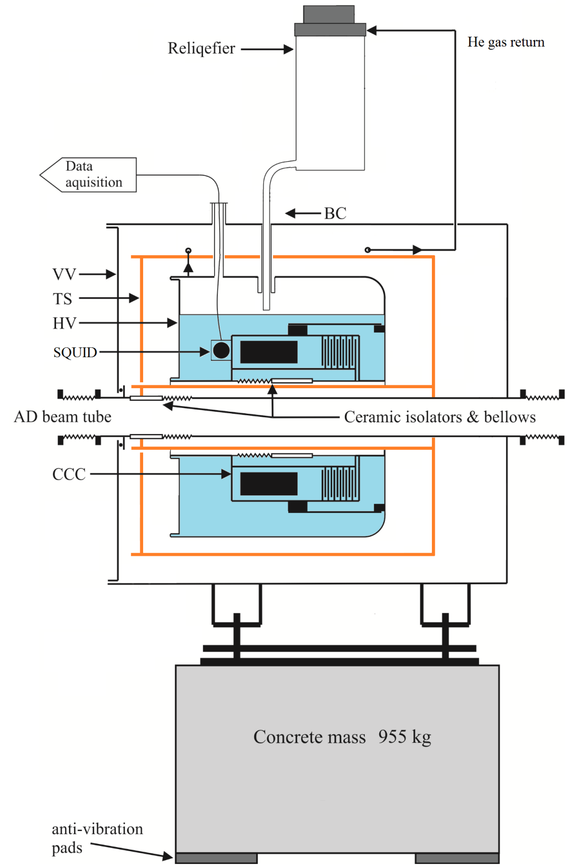

Figure 3: CCC cryostat schematic.

A PLC-based system has been implemented to monitor and control the cryostat status and is independent of the CCC beam diagnostic acquisition and control system.

ACQUISITION AND CONTROLS

The data acquisition system used for control and measurements is based on the VME standard and comprised of a MEN-A20 CPU card, a VD80 ADC card, and a CTRV CERN timing receiver. The CPU card hosts a dual core INTEL Core 2 Duo L7400 64-bit processor running at 1.5 GHz

ISBN 978-3-95450-177-9

with 4 GB of RAM. The VD80 ADC card enables the simultaneous sampling of 16 channels (16 MB per channel) with a 16-bit resolution, an input range of ±10 V (differential) and a maximum acquisition frequency of 200 kHz. The currently used sampling rate is set to 1 kHz. The CTRV is a CERN timing receiver used to provide information and triggers, for both software actions and TTL hardware outputs, on the arrival of accelerator timing events.

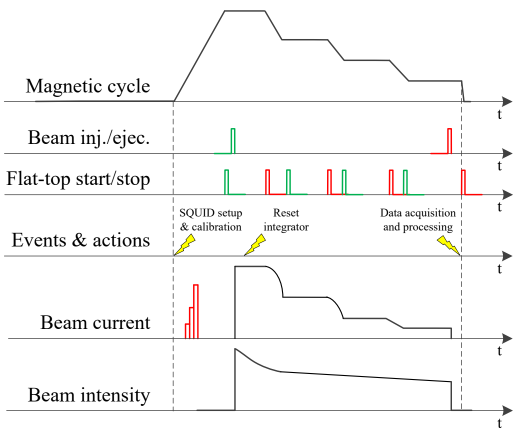

Figure 4: Actions and events during the AD cycle acquisition.

The time diagram representing the main events, triggers and actions performed during an AD cycle are depicted in Fig. 4. The acquired time markers register the TTL output signal of the CTRV card at beam injection, at the start of each magnetic cycle flat-top and at the end of each magnetic flat-top. The injection event is used in real-time for re-setting the SQUID integrator in order to ensure a zero offset and guarantee sufficient dynamic range for the current measurement. Furthermore, the flat-top markers are subsequently used to automatically detect the beginning and the end of each phase time window for which intensity measurements are particularly relevant for the operators.

A real-time server, running on the VME-based CPU card, has been developed in order to automate the configuration, calibration, acquisition and publishing of the measurements. The software architecture of this server is based on the CERN Front-End Software Architecture (FESA) C++ framework [10]. The SQUID and the current source used for the calibration support a serial communication interface. This serial interface to both devices is currently proxied using a serial device server converting to TCP-based socket communication. The FESA server implements the instruction protocols used to configure these devices according to the user settings. These settings include important SQUID configuration parameters such as the bias current, bias voltage, gain bandwidth and feedback resistance when running in FLL mode (see Fig. 2), to name a few. It also allows the expert to configure and trigger the precision current source used for the automatic calibration of the system, something that is performed at the beginning of each cycle of the AD machine.

The FESA server also implements the post-processing algorithms which entail offset correction, the detection of the current calibration steps, the linear fit to estimate the calibration factor, the computation of the revolution frequency based on the magnetic cycle and the computation of the number of charges from the current measurement and the inferred revolution frequency. These results are then made available to experts and operators via CERN's standard controls middleware infrastructure.

BEAM MEASUREMENTS

The first AD beam measurements with the CCC were obtained during the 2015 run [8]. Two main limitations in the beam current measurement were observed. The current resolution was limited to $\sim$ 300 nA, mainly due to strong perturbations at 50 Hz and harmonics, and an offset jump was seen to occur at injection, due to the SQUID/FLL feedback loop locking to a different working point. This latter effect be caused by a combination of excessive slew-rate of the input signal and excessive flux noise/perturbations coupled to the SQUID [2, 6].

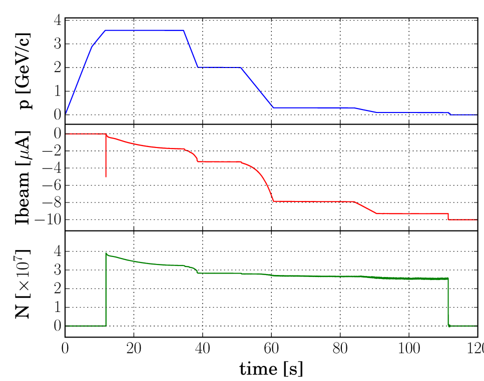

Figure 5: Measurement of the AD cycle beam current in red (middle) and intensity in green (bottom), with the particle momentum shown in blue (top).

It was suspected that the excess noise and perturbations could be due to currents passing through the RF-bypass installed in the ceramic gap of the beam pipe (see Fig 2). This was originally included in order to improve the SQUID/FLL stability by reducing the beam signal slew-rate. For the 2016 run the RF-bypass was removed leaving an isolated ceramic gap. This resulted in a significant reduction in the noise, enabling current measurements with a resolution as low as $\sim$ 3 nA to be achieved. This allowed for a total dynamic range of 85 dB. Consequently, the beam intensity measurement was also improved showing a resolution of $0.0012 \times 10^7\ \bar{p}$ when $\beta = 0.967$, and $0.013 \times 10^7\ \bar{p}$ when $\beta = 0.106$. An example of the measurement of an AD cycle with this improved performance is shown in Fig. 5. The flux-jump at injection, however, still occurs. In order to compensate for this a reset of the SQUID/FLL is performed right after injection. This way it is possible to obtain a relative measurement of the cycle efficiency in real-time while the

ISBN 978-3-95450-177-9

absolute measurement is obtained after the cycle is complete by calculating the zero current baseline after beam ejection.

With the acquisition and control system for the CCC in place, it was possible to consistently acquire data for many AD cycles, making it available to perform a first statistical analysis of the CCC measurement parameters. Fig. 6 shows the histogram of current resolution $\sigma(I_{\text{beam}})$ for more than 4500 cycles. It can be seen that for the majority of the acquired cycles $\sigma(I_{\text{beam}}) < 10\,\text{nA}$, with a peak at $\sim 3\,\text{nA}$. The principal cause for the large tail in $\sigma(I_{\text{beam}})$ was seen to be the noise from pressure fluctuations in the HV caused by thermoacoustic oscillations. This can eliminated by proper adjustment of the cryostat settings. An analysis of the baseline variation during a cycle was also performed by looking at cycles where no beam was injected. A histogram of the maximum drift of the baseline within a cycle is shown in Fig. 7. Except for a small number of cycles, the baseline drifts by $< 50\,\text{nA}$. These long-term variations are again thought to be mainly caused by variations of the pressure in the HV of the cryostat.

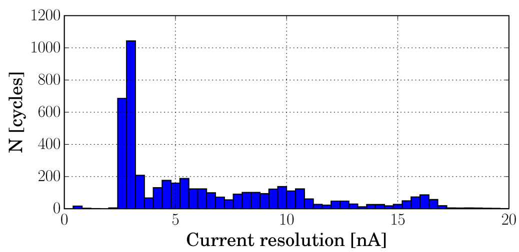

Figure 6: Distribution of the current resolution for 4685 acquired cycles.

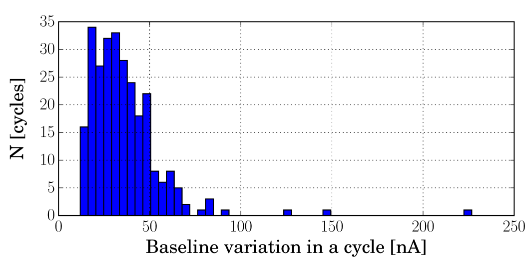

Figure 7: Distribution of the baseline drift for 271 acquired cycles where no beam was injected.

CONCLUSIONS

A CCC monitor with complete acquisition system has been developed and installed in the AD. Beam measurements obtained during the first half of 2016 show significant improvements in the current resolution when compared to results obtained in 2015. The current implementation of the CCC monitor has been able to provide a beam current measurement with resolutions down to 3 nA. This performance was possible even with the cryocooler reliquifier running and supplying LHe to the cryostat. This was only possible due to the careful design of the cryostat to suppress most mechanical vibrations. This is the first fully operational CCC system able to continuously measure both bunched and coasting beams in a synchrotron accelerator.

Statistical analysis of the monitor performance reveals that the drift of the baseline may have a considerable contribution to overall accuracy, with correction techniques needed to compensate for this, e.g. by implementing a deconvolution for effects of pressure and temperature variations. These signals are already being acquired by the acquisition system. It should, however, be noted that for many of the cycles acquired for this analysis, the settings in the cryostat were still being tested and adjusted, and that steady-state functioning had not yet been reached.

ACKNOWLEDGEMENT

The authors acknowledge the outstanding work of CERN's Central Workshop (EN-MME), Cryogenic group (TE-CRG), Vacuum group (TE-VSC) and AD operations (BE-OP) who assisted in the design, manufacture, assembly and installation of the CCC cryostat. Fruitful discussions with Patrick Odier, Jeroen Belleman, Manfred Wendt, Henry-Jobes Barthelmess and Dietmar Drung are gratefully acknowledged.

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement number 289485.

REFERENCES

[1] P. Odier, CARE-CONF-2004-023-HHH. P. Odier, "DCCT technology review," C04-12-01.1, Proceedings of CARE-HHH-ABI.

[2] M. Fernandes *et al.*, "A Cryogenic Current Comparator for the Low Energy Antiprton Facitilities at CERN," in *Proc. IBIC'14*, Monterey, CA, USA, paper WEPF04, 2014.

[3] I.K. Harvey, *Rev. Sci. Instrum.* 43 (1972) 1626.

[4] A. Peters *et al.*, "A cryogenic current comparator for the absolute measurement of nA beams," BIW98, Standford, May 1998, (p. 163), AIP conference proceedings.

[5] K. Grohmann *et al.*, *Cryogenics* 16(10) (1976) 601.

[6] D. Drung, "High-performance DC SQUID read-out electronics," *Physica C: Superconductivity*, Vol. 368, Issues 14, 1 March 2002, 134-140.

[7] R. H. Koch, "Maximum theoretical bandwidth and slewrate of a dc SQUID feedback system," *IEEE Transactions on Applied Superconductivity* 7(2), p. 3259 (1997).

[8] M. Fernandes *et al.*, "Cryogenic Current Comparator for Low-Energy Antiproton Facilities at CERN," in *Proc. IBIC'15*, Melbourne, Australia, paper MOPB043, 2015.

[9] A. Lees *et al.*, "Design and optimisation of low heat load liquid helium cryostat to house cryogenic current comparator in antiproton decelerator at CERN," ICEC 2016 Conference, 9-P2-111, New Delhi, India, 2016.

[10] M. Arruat *et al.*, "Front-End Software Architecture," in *Proc. ICALEPCS'07*, Knoxville, TN, USA, paper WOPA04, 2007.

ISBN 978-3-95450-177-9