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Superconducting Beam Charge Monitors for Antiproton Storage Rings

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A Cryogenic Current Comparator (CCC) is a new type of instruments for monitoring charged beams like ions or antiprotons. Using superconducting effects is it possible to create a nondestructive, contactless and easy to calibrate beam measurement system with a high current resolution in amplitude and time. The Meissner effect enables an effective magnetic shielding of the system. The screening current enables creation of DC-transformers and therefore a DC-current measurement system. The combination of two Josephson-junctions and coils form a superconducting quantum interference device (SQUID) in an analog magnetic feedback of the flux-locked loop (FLL), which is linearizing the SQUID's transfer function. The performance of the CCC system opens beam currents range between 1 nA and 20 μA. Installations at the Antiproton Decelerator at CERN and GSI in Darmstadt shows a strong correlation between SEM / longitudinal-Schottky and CCC signals including the known spill pattern but with a better signal to noise ratio.

KEYWORDS: beam monitoring, cryogenic current comparator, CCC, superconducting quantum interference device, SQUID, spill pattern, CERN, GSI

1. Introduction

A precise absolute measurement of beam intensity respectively number of particles delivered to the experiment is required in storage ring experiments for the determination of reaction rates of any kind of recombination or dissociation experiments. Conventional beam intensity monitors like DC Current Transformers (DCCT) are not suitable for beam currents between 1 nA and 20 μA due to their noise limited resolution of 1 μA/sqrt(Hz) and a frequency response of up to 10 kHz [1]. Schottky detectors are well established in storage rings but have some drawbacks monitoring the average beam current due to their calibration regime. A Cryogenic Current Comparator (CCC) system developed for application in particle accelerators by FSU Jena and GSI is currently installed in the

Antiproton Decelerator at CERN, another advanced CCC for the FAIR project at GSI is under construction and will be installed in CRYRING. This contribution will give an overview on the superconducting quantum interference based working principle and the fractions of nA/sqrt(Hz)-performance of the CCC systems [2].

2. Superconducting effects

2.1 Shielding

The environment of accelerator, decelerator or storage rings is full of electromagnetic interferences and the measured magnetic field induced by currents in nano amps range is very low. Normal conductors are well-known for the shielding of radio frequencies and electrostatics. Static and low frequency magnetic fields are not so easy to suppress. Thick layers of Mu-metal, a nickel–iron soft magnetic alloy, can reduce the field intensity. However, a superconducting shield solves the problem as shown in Fig. 1.

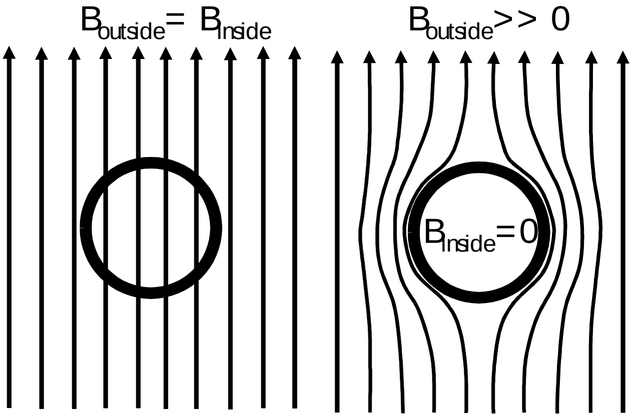

Fig. 1. Magnetic field B behaviour of:
Left: a normal-conductor – the field is inside,
Right: a super-conductor – no field inside.

2.2 DC transformer

Impedance matching is very important for an optimal signal to noise ratio. Typically transformers are used to achieve a matching between source and drain. Unfortunately, a normal transformer works only with an AC-mode following the law of induction. In a superconducting circle a static magnetic field leads to a constant screening or shielding current. In this way, a superconducting transformer works in AC- and DC-mode as shown in Fig. 2. Therefore a DC-sensor can be created. The first transformer will be built by a nanocrystalline, high-permeability core as flux concentrator, a "one-turn" input coil created by the charged beam itself and the real one-turn pick-up coil. The inductance is in the range of 50 µH and 100 µH at liquid helium temperature. A second transformer is

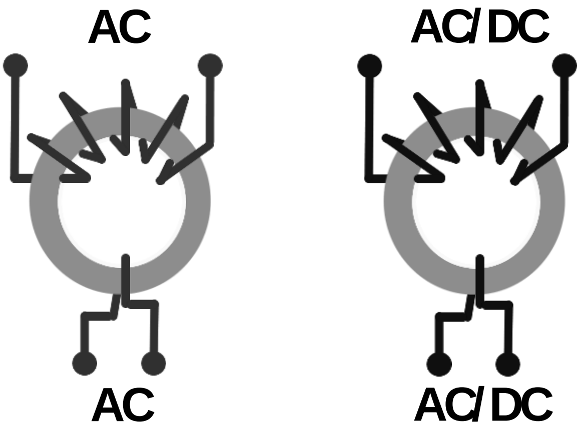

Fig. 2. Left: Normal-conductor transformer – only AC transformation possible.

used for the matching between pick-up coil and the low input of the superconducting quantum interference device (SQUID).

2.3 Superconducting Quantum Interference Device (SQUID)

The connection of two superconductors by a weak link is known as a Josephson junction (JJ). The combination of two JJ's leads to a DC-superconducting quantum interference device (DC-SQUID) with strong magnetic field dependence in the voltage-current curve as shown in Fig. 3. This dependency is periodically relating to the magnetic flux. The cycle range is the fundamental physical constant the magnetic flux quantum $\Phi_0 = 2.067\ 833\ 831 \cdot 10^{-15}$ Tm^2 [3]. A small coil on the secondary side of the matching transformer couples the flux of the charges beam into the DC-SQUID. An additional coil with a controlled current compensates that flux in a way that the SQUID is locked in an operation point. This mode is called flux locked loop (FLL).

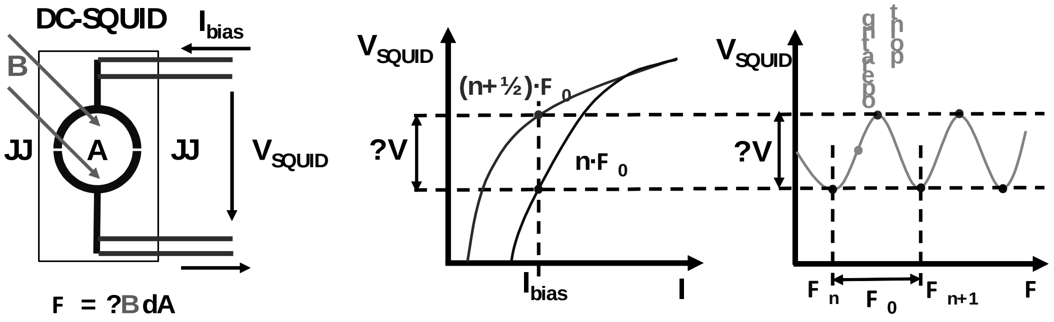

Fig. 3. Left: Schematic of a DC-SQUID with four-wire measurement.
Middle: Voltage-current-diagram and the magnetic flux dependence.
Right: Voltage-flux-diagram and creation of an operating point for the linearizing via FLL.

2.4 Cryogenic Current Comparator (CCC)

Figure 4 shows the principle of the CCC system as a nondestructive, contactless current measurement system using the magnetic field of the moving charged particles. The necessary compensation current of the FLL becomes the measurement value of the beam current. The complete CCC sensor system in the beamline is shown in Fig. 5. The shielding and filtering of beam magnetic field component is realized as a meander structure. Naturally a cryostat is necessary to ensure the low temperature for the superconductivity by the use of liquid helium.

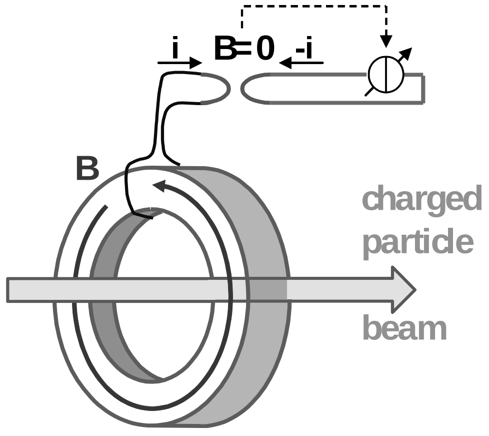

Fig. 4. Principle of a CCC system.

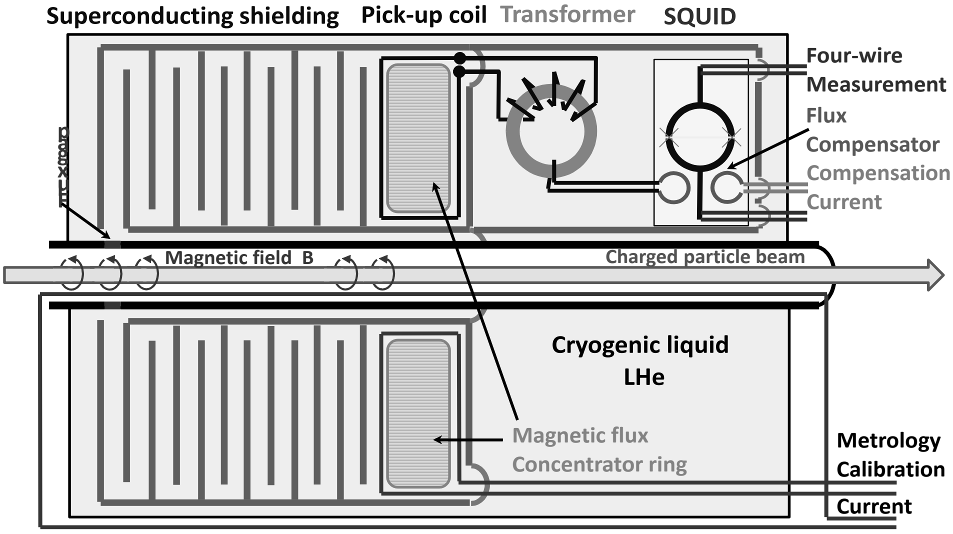

Fig. 5. Left: Schematic of a CCC sensor system with cryostat, shielding, DC-transformers DC-SQUID, flux compensation and calibration coils.

3. CCC measurements

3.1 Intensity Calibration

The CCC system makes it easy to calibrate measurements via calibration coils through the beam hole or flux concentrator ring with a well-defined current signal. Figure 6 shows the linear correlation between CCC and secondary emission monitor (SEM) signal with a slope of 0.8 measured at GSI [3].

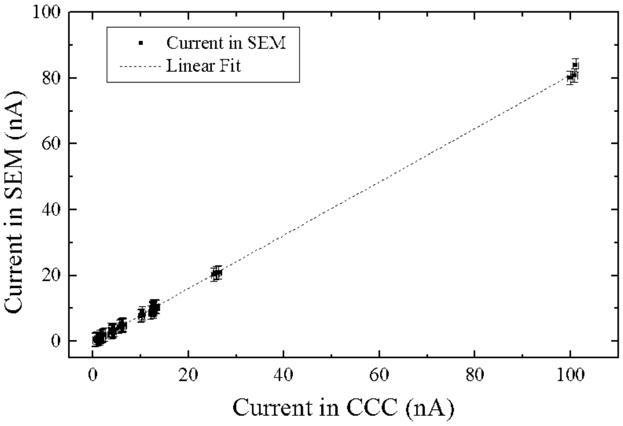

Fig. 6. Linear correlation between CCC and SEM [3].

3.2 Time resolution

The known spill structures of beams are a real scenario to test the CCC performance in comparison to well-established beam measuring systems like SEM. Figure 7 shows the spill structure of a measured Ni^{26+} ion-beam (intensity $1.69 \cdot 10^9$) slowly extracted from accelerator SIS18 (GSI-SchwerIonenSynchrotron 18) over an extraction time of 200 ms. To reduce the noise in SEM output, both signals are filtered by a 2 kHz low-pass. It is clearly recognizable that under same conditions the spill structure is identically and the CCC signal has a lower noise level. Using additional filtering at the pick-up coil level is it also possible to low-energy antiprotons as shown by Fernandes in comparison to longitudinal-Schottky sensor at CERN [4].

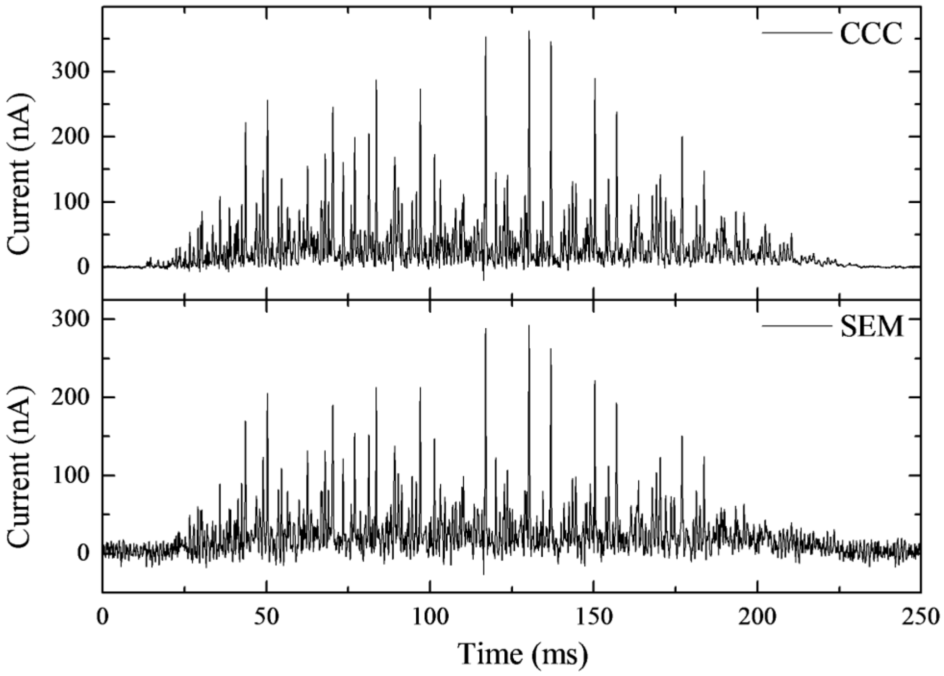

Fig. 7. Spill structure of a slowly extracted ion beam measured with a CCC- and a SEM-system

4. Conclusion and outlook

Superconducting effects like ideal magnetic shielding, DC-transformer and the quantum interference of Josephson junction enable the creation of an outstanding beam monitoring system – the CCC. It is tested in the beam lines like GSI-SIS18. The spill structures of extracted ion-beams could be measured with high temporal and current resolution. The CCC can be easy calibrated and also be used for the calibration of other devices like SEM. In the next generation of CCC-systems new core materials will reduce the current noise and will be increase the bandwidth. Especially the lager diameters of newer beamlines with new cryostat designs are a challenge. Special low pass filters, digital data processing and fast coreless versions can extend the application field of the CCC-systems.

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