Review of the Experimental Results with a Cryogenic Current Comparator

A. Peters, H. Reeg, C.H. Schroeder, GSI, Darmstadt, Germany
W. Vodel, H. Koch, R. Neubert, H. Mühlig, University of Jena, Germany

Abstract

A new type of beam transformer, using the principle of a Cryogenic Current Comparator, was built to measure extracted ion beams from the SIS, the heavy ion synchroton at GSI. A current resolution of 0.1-0.3 nA/$\sqrt{Hz}$, depending on the frequency range, could be achieved which allows to measure ion beams with intensities greater than 10^9 particles per second with high accuracy. Numerous investigations were carried out to study the zero drift of the system which shows a strong exponential slope with two different time constants. Furthermore the microphonic sensistivity of the system was studied by taking noise spectra of the detector output signal. Additional measurements were made with a vibration sensor to separate the horizontal and vertical components of the mechanical influences from the disturbing electrical interferences. The recent results - including the first tests with ion beams - will be presented in this paper.

1 THE DETECTOR SYSTEM

1.1 The Measuring Principle

A non-destructive method was sought for measuring the intensity of extracted ion beams from the GSI synchroton in the region above 10^9 particles per second (pps). Beam transformers of the fluxgate type can measure in a non-destructive manner and with a bandwidth from dc to several kHz, but their resolution only reaches one μA. Therefore a much more sensitive measuring principle was chosen – a Cryogenic Current Comparator (CCC), first developed by Harvey (National Standards Laboratory, Sydney, Australia) for precise dc current ratios in 1972 [1]. To compare two currents with high precision he used a superconducting meander shaped flux transducer. Only the azimutal magnetic field component, which is proportional to the current in the wires, will then be sensed by the pick-up coil – all other field components are strongly suppressed. The very small magnetic flux coupled into the coil were detected by an RF-SQUID.

A further device for beam intensity measurements using the CCC-principle achieved a current resolution of about 10 nA, but the stability was inadequate due to the installed RF-SQUIDs and other technical difficulties [2].

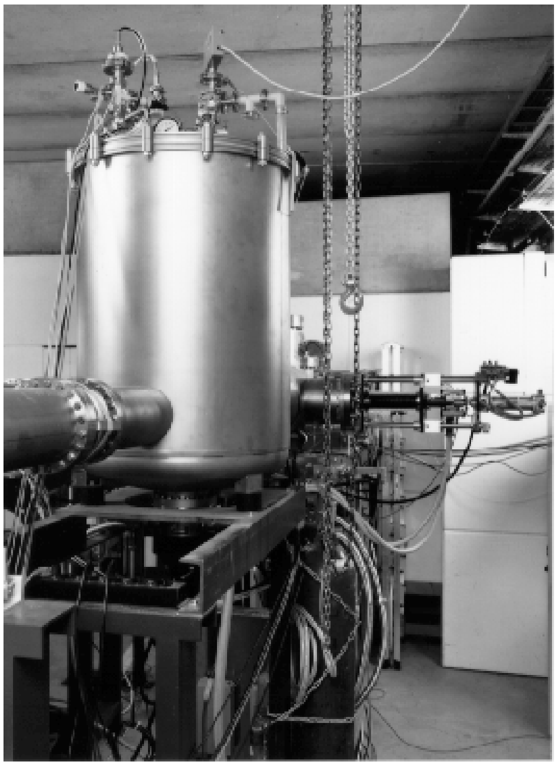

Figure 1: Cryostat with detector system built in the beam line of the beam diagnostics test facility (Photo: Achim Zschau, GSI)

1.2 The Construction of the Detector

Some new techniques were used in our concept [3] to solve the problems that occured in the PTB-device [2]. The main components of the detector (see fig. 1) are

- the superconducting flux transducer made of lead tubes and plates isolated by Teflon foil; the attenuation of all non-azimutal magnetic field components was designed and calculated to realize a level of 10^{-9},
- a superconducting flux coupling coil as the antenna for the ion beam, consisting of a superconducting niobium toroid with a VITROVAC 6025-F core (VAC GmbH, Hanau, Germany),
- a coupled d.c. SQUID system made by the Friedrich-Schiller-University of Jena as the extremely high sensitive magnetic flux sensor (noise limited sensitivity:

$4{\cdot}10^{-6}\ \phi_0/\sqrt{Hz}$) with a modulation frequency of 125 kHz and a measuring bandwidth of nearly 10 kHz,

- a special LHe-bath-cryostat with a "warm hole" of Ø 100 mm for the passing ion beam; the outer heat shield consist of a superinsulated copper vessel cooled down to 35 K by a refrigerator .

2 THE PERFORMANCE OF THE CCC

2.1 The Current Resolution

After testing and assembling of all parts of the detector measurements concerning the current resolution and the noise limitations were started with. To simulate the ion beam a simple wire loop (one winding) around the flux transducer was installed. Using a calibrated picoampere current source (KEITHLEY 261) the current sensitivity was measured. Fig. 2 shows the output of the SQUID electronics as a function of the calibration current. The current sensitivity of the detector system was determined to 177.3 nA/ϕ_0 the linearity error is smaller than 0.5 %; 1 ϕ_0 corresponds to an output signal of 2.5 V in the most sensitive range of the SQUID system. During the measurements the refrigerator was switched off to avoid microphonic effects (see below). To determine the current resolution of the system several noise spectra from 10 Hz to 20 kHz were recorded. The measured noise levels of 0.08-0.9 mV$_{RMS}$, depending on the frequency range, correspond to current resolutions of 0.05-0.5 nA/$\sqrt{Hz}$.

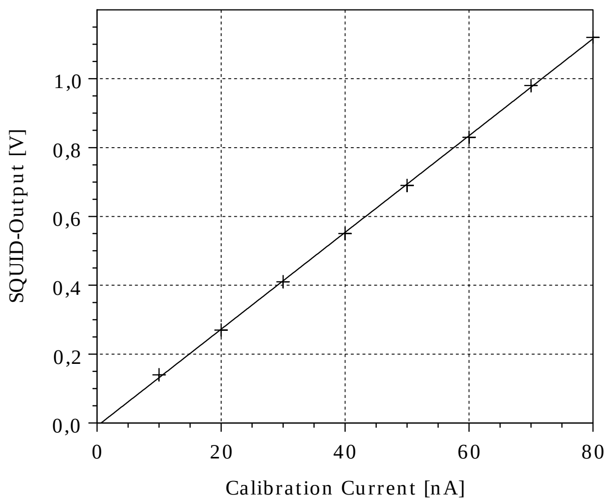

Figure 2: Plot of current calibration data

2.2 The Zero Drift

At the beginning of each test the output signal of the SQUID system shows a strong zero drift. It was supposed that remanent flux in the core of the coupling coil fades away because of imperfect superconducting contacts in the input circuit. To study this effect the detector was cooled down to 4.2 K over a period of about 100 hours. The results of the long-term observation are shown in fig. 3. The curve is fitted by the sum of two exponential functions where the time constants are 11.6 h and 2.4 h. The second time constant may be caused by a thermal effect. After a cooling time of about 100 hours the zero drift drops to values under 0.5 mV/s (≅ 35 pA/s current drift), during another test run a minimum value of 0.23 mV/s (≅ 16 pA/s current drift) was achieved.

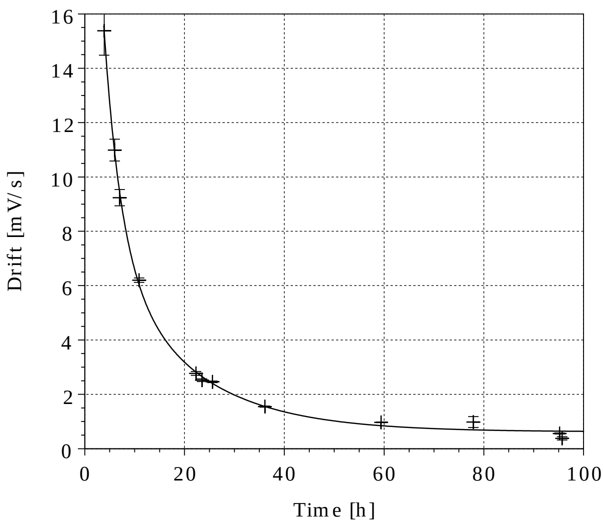

Figure 3: Measurement of the zero drift

2.3 Influences of Magnetic Background Fields

Further measurements were carried out to study the influence of external magnetic fields. A field of 10^{-5} T yields the following apparent currents:

$$\vec{B} \parallel \vec{I} \quad 3.3\ \text{nA}$$

$$\vec{B} \perp \vec{I} \quad 22\ \text{nA}.$$

These values are 1–2 orders of magnitude higher than expected, but small enough to allow tests under real conditions in the beam line of the beam diagnostics test stand.

2.4 Microphonic Sensitivity

Furthermore numerous investigations were carried out to study the microphonic sensistivity of the detector system. Therefore the refrigerator must be switched off because of the strong mechanical influence of the Gifford-McMahon machine. If vacuum pumps close to the detector are switched on during the measurements, an inevitable mechanical influence in an accelerator environment besides vibrations of the building, the noise spectrum shows several characteristic lines. Besides the disturbing electrical interferences (50 and 100 Hz) there are peaks in the region of 16 – 18 Hz, 43 Hz, 74 Hz, 85 Hz and 98 Hz, which are caused by mechanical resonances of the dewar. In the higher-frequency region only an interference at 987 Hz with harmonics was observed.

The results of the measurements were taken into account for the design of the vibration insulated installation of the detector in the test beam line. The device is mounted on three rubber bearings, vibrations on the beam pipe are damped by metal bellows on each side of the CCC.

3 TESTS WITH ION BEAM

3.1 First Measurements

At the beginning of May 1996 first measurements were carried out with a $^{20}Ne^{10+}$-ion-beam that was accelerated to 300 MeV/u in the SIS. About 3-4$\cdot 10^{10}$ particles in the machine were extracted over a time of 2 or 3 seconds resulting in average electrical currents of 8-12 nA; the transmission to the beam diagnostics test facility was about 50 %. An example of a typical measurement, taken with the full bandwidth of about 10 kHz, is given in the upper trace of fig. 4. The extracted ion beam shows a strong modulation

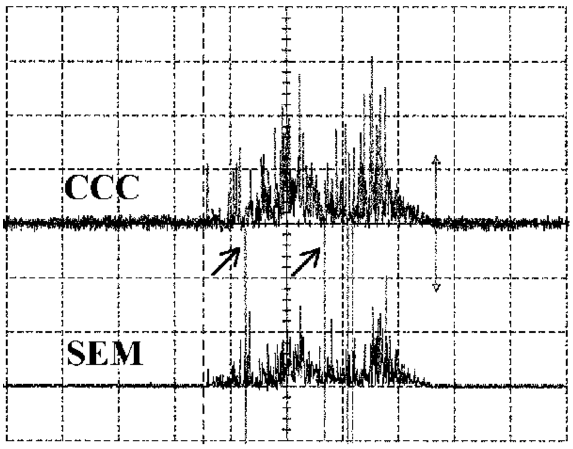

Figure 4: Measured ion current pulse extracted from the SIS; x-axis: 500 ms per div., y-axis: 0.5 V per div. ($\cong$ 35.5 nA ion current per div. for the CCC)

with current peaks up to 100 nA while the average current is about 12 nA. Because of this spill structure we found that the current rise time occasionally exceedsthe slew rate of the measuring system. In those cases the feedback circuit of the CCC becomes unstable and negative spikes and other unpredictable effects could be observed (see markers in fig. 4).

The practical value for the noise limited current resolution, depending on the selected frequency range, lies between 0.1-0.3 nA/$\sqrt{Hz}$ – a factor of 1000 better than that of a beam transformer of the fluxgate type.

3.2 Comparison with SEM

A secondary electron monitor (SEM) [4] made of three Al plates is mounted closely behind the CCC to have a comparable measuring device. The bandwidth of the coupled current amplifier was chosen to be similar to that of the CCC (about 10 kHz). The output of the SEM is shown in the lower trace of fig. 4. The shape of both signals is similar and the quantitative correspondence is remarkable:

Particles in the SIS	Extraction time	Measured particles
$3.7 \cdot 10^{10}$	2s	$1.51 \cdot 10^{10}$ (CCC) $1.62 \cdot 10^{10}$ (SEM)
$3.5 \cdot 10^{10}$	3s	$1.66 \cdot 10^{10}$ (CCC) $1.58 \cdot 10^{10}$ (SEM)

The difference between the measured particles of the CCC and the SEM is only in the order of 5-7 %.

For the determination of the particles measured by the SEM the energy loss of the ions inside the Al material is calculated using the Ziegler formalism [5]. For the specific yield – the amount of detectable secondary charge per unit energy loss – a formula was used that shows a slight dependence on the nuclear charge of the incoming ions [6]. Further comparative measurements at various energies are necessary to verify this behaviour.

4 CONCLUSION

The first tests of the CCC show that this type of detector can be used as a non-destructive and absolute calibratable device for intensity measurements of (ion) beams with electrical currents greater than 1 nA. To eliminate the small zero drift an automatic offset correction will be useful. Furthermore careful investigations have to be made to minimize environmental influences like vibrations and disturbing magnetic fields.

The GSI prototype will now be improved with regard to a larger bandwidth to allow more studies about the time structure of intense extracted ion beams.

5 REFERENCES

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