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Gesellschaft für Schwerionenforschung mbH
Planckstraße 1 • D-64291 Darmstadt • Germany
Postfach 11 05 52 • D-64220 Darmstadt • Germany

Absolute Measurements and Analysis of nA-Ion Beams

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

1 THE DETECTOR SYSTEM

A variety of detectors are used to measure proton and heavy ion beam currents [1]. Especially in the range between 50-2000 MeV/u nearly all detector principles (e.g. ionization chambers, secondary emission monitors) are based on beam-material interaction so that the beam will be more or less distorted due to energy loss and emittance growth by particle scattering. Only beam transformers can measure in a non-destructive manner. The fluxgate type transformers have a bandwidth from dc to several kHz, but their sensitivity only reaches some μA.

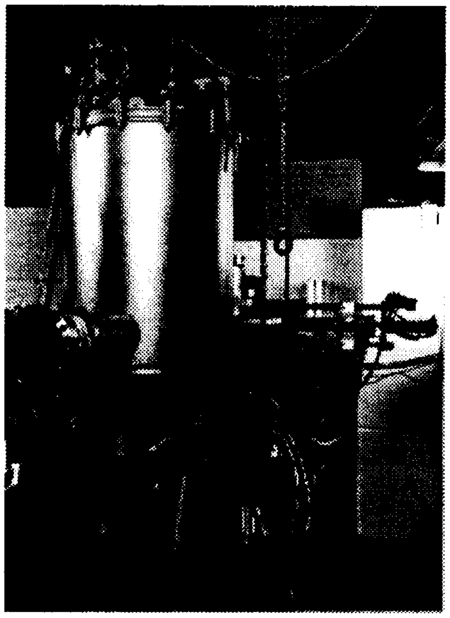

Figure 1: Cryostat with detector system built in the beam line of the beam diagnostics test facility (Photo: Achim Zschau, GSI)

Therefore a much more sensitive measuring principle was chosen – a Cryogenic Current Comparator (CCC), developed first by I. K. Harvey (National Standards Laboratory, Sydney, Australia) for precise dc current ratios in 1972 [2]. To compare two currents with high precision he used a superconducting meander shaped flux transducer. Only the azimuthal 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 was detected at that time by an RF-SQUID.

In our case the beam replaces one winding of the comparator. In connection with some new techniques a design concept [3] was found to solve the problems that occured in formerly built devices [4, 5]. The main components of the detector are a superconducting flux transducer, a superconducting flux coupling coil and a coupled d.c. SQUID system (developed and fabricated by the Friedrich-Schiller-University, Jena) as the extremely high sensitive magnetic flux sensor [6]. These detector parts are mounted in a special LHe-bath-cryostat with a "warm hole" of 100 mm in diameter for the passing ion beam (see fig. 1).

The main properties of the detector are listed up in the following table.

Property	Achieved Value
Current sensitivity	173.1 nA/ϕ_0 (1 $\phi_0 \cong$ output signal of 2.5 V)
Noise level	0.08–0.9 mV$_{RMS}$ ($\cong$ 0.05-0.5 nA/$\sqrt{Hz}$), depending on the freq. range
Bandwidth	0–10 kHz
Current zero drift	$\leq$ 0.5 mV/s ($\cong$ 35 pA/s) after a cooling time of 2 days
Influence of external magnetic fields (apparent currents)	0.33 nA/μT ($\vec{B} \parallel \vec{j}$) 2.2 nA/$\mu$T ($\vec{B} \perp \vec{j}$)

2 MEASUREMENTS OF ARGON AND NEON BEAMS

Since May 1996 the detector was used in four beam times at GSI's heavy ion synchroton facility to measure extracted ion currents (neon and argon beams) of 10 - 30 nA, having an accuracy of a few percent . To achieve such a precision a special, but very simple calibration technique was developed. The isolated calibration winding used in each beam transformer is mounted here on the surface of the flux transducer lying in liquid helium with it's main part. This avoids thermally caused leak currents. In addition, this winding was manufactured from Zeranin®, a material with a very small temperature gradient of the specific resistance. A typical calibration curve can be found in fig. 2, which shows a very good linear dependency of the SQUID-output voltage with respect to the input current.

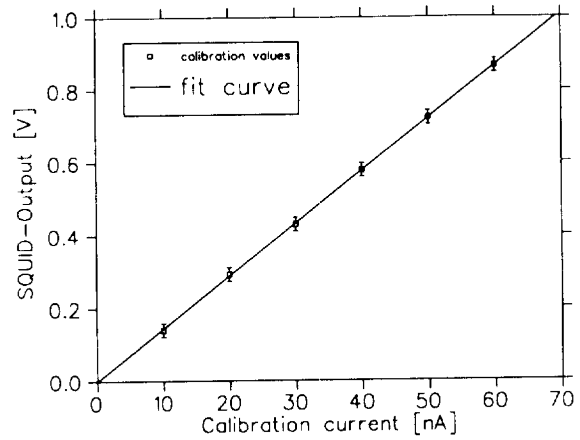

Figure 2: Calibration curve of the CCC

Using this calibrated CCC detector system it is possible now to measure the extracted ion currents directly. In the next three years it will be mainly used for the high current calibration of SEMs [7] which are mounted in nearly all high energy beamlines at GSI. Fig. 3 shows such a calibration curve for 300 MeV/u ^{20}Ne^{10+} beam simultaneously measured by both detetors. A similar curve was measured for a 720 MeV/u ^{40}Ar^{11+} beam. The gradients of these curves have to be compared to calibration factors measured at lower beam currents and theoretical values [7].

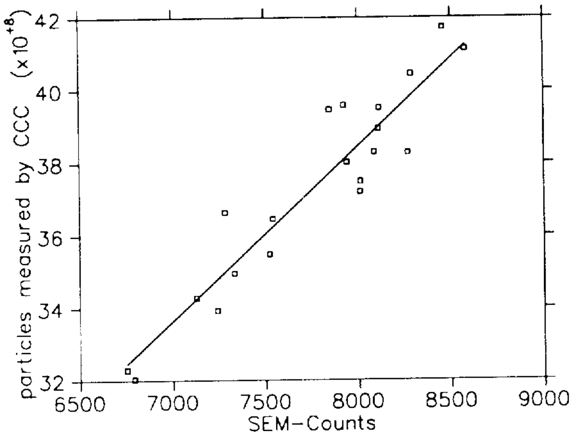

Figure 3: Calibration curve for a 300 MeV/u ^{20}Ne^{10+} beam measured by the CCC and a SEM simultaneously; each point is one spill.

3 SPILL TIME STRUCTURE ANALYSIS

Besides the absolute measurement of the beam current, one can derive more information from the CCC signals. The detector's bandwidth of 0–10kHz permits fundamental investigations concerning the time structure of the extracted ion beam. In fig. 4 the macro- and microstructure of a single spill is shown. A strong modulation with current peaks up to 130 nA is evident while the average current is only about 15 nA. The beam consists of individual bursts with a steep rise and a more gentle slope. This behaviour was predicted last year by simulations of the extraction process by M. Pullia [8], see fig. 5.

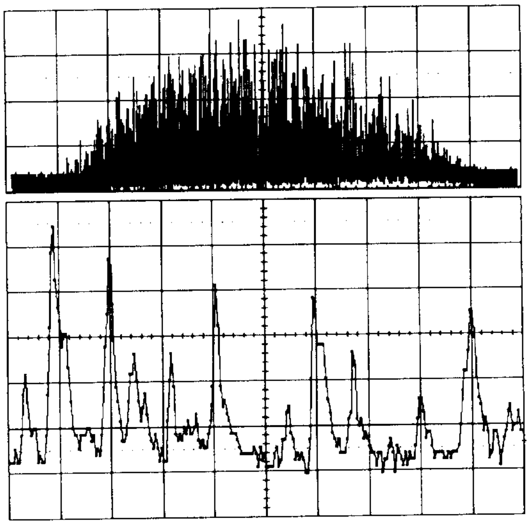

Figure 4: Measured ion current extracted from the SIS; top: full spill signal, x-axis: 200 ms per div., y-axis: 0.5 V/div. (≅ 35 nA ion current); bottom: detail of the spill, x-axis: 0.5 ms/div., y-axis: 0.21 V/div. (≅ 15 nA ion current).

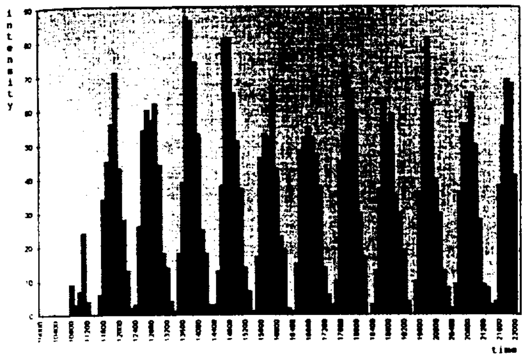

Figure 5: Simulation of an extracted beam from a synchroton; a monochromatic beam with a 2 kHz ripple on the power supplies is assumed; from [8].

But the current rise time of this spill structure sometimes exceeds the slew rate of the measuring system, if the value goes beyond 5000 ϕ_0/s (≅ 1 nA/μs). In those cases the feedback circuit of the CCC electronics becomes unstable and negative spikes and other unpredictable effects could be observed [6].

The power spectrum of a single spill shows further details of its structure (see fig. 6). Strong, but very narrow lines at 150, 600, 1200 Hz and the corresponding harmonics have their reason in ripple of the synchroton magnet power supplies. The continuous frequency spectrum shows a strong drop from 0–1000 Hz followed by a more flat region up to 7 kHz where the spectrum seems to end. This behaviour is not yet understood and further investigations in connection with theoretical calculations are needed.

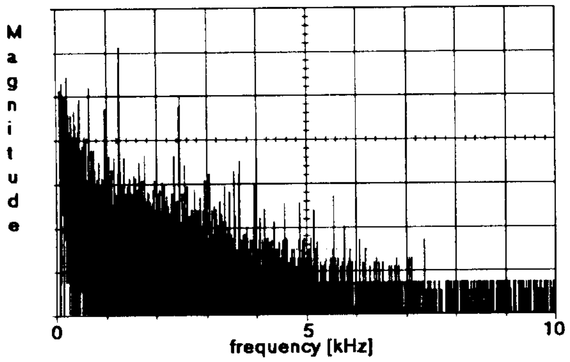

Figure 6: Power spectrum of a single spill (vertical scale: arb. units)

4 FURTHER DEVELOPMENTS

Further developments on the SQUID-electronics and the cryogenic equipment of the detector system are necessary. To avoid the instabilities in the feedback circuit (see above) a new version of the SQUID-electronics is in preparation. The development aims at a higher slew rate combined with an enlarged bandwidth. In addition, an automatic offset correction will be installed to minimize the zero drift during a typical measurement interval of 1-10 s.

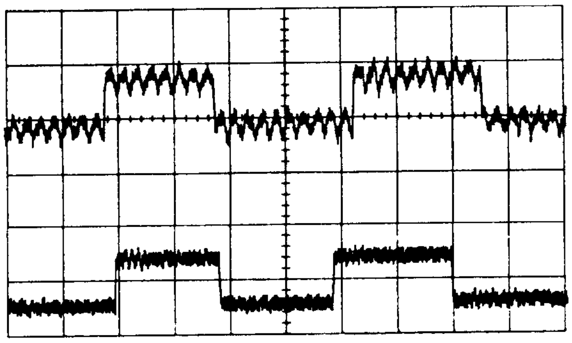

Figure 7: 30 nA calibration pulses; upper trace: pulse tube cooler switched on; lower trace: pulse tube cooler switched off; x-axis: 500 ms/div., y-axis: 0.5 V/div.

On the other hand the detector's cooling setup has to be modified so that it is possible to measure for a typical beam time period of 6-8 weeks without handling any liquid helium. For this purpose the use of a "Quantumcooler" [9] will be checked, which is able to eliminate the helium boiloff. For the cooling of the outer radiation shield we used a Gifford-McMahon refrigerator until now. But this device has to be switched off, otherwise no measurement was possible because of the strong vibrations. Recently we installed a prototype of a pulse tube cooler [10] to avoid this disturbances. The first result is shown in fig. 7. The remaining interference consists of a ripple dominated by the first harmonic of the cooler's 4 Hz driving frequency, but such a superimposed modulation on the measurement signal can be suppressed by special electronic equipment [11].

5 CONCLUSION

The first measurements with the CCC show that this new type of device can be used as a non-destructive and absolute calibratable detector for intensity determination of (ion) beams with electrical currents greater than 1 nA. Furthermore the detector allows useful investigations of beam structures up to 10 kHz or more, only limited by the performance of the SQUID electronics.

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