A Cryogenic Current Comparator for Nondestructive Beam Intensity Measurements

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Abstract

In the course of the next few years the extracted beam intensities of the SIS (the heavy ion synchroton at GSI) will reach 10^{11} particles per second, corresponding to beam currents up to the μA-range. Especially in the region above 1 nA a non-destructive and calibratable measurement is required to determine extraction efficiences in regular intervals. Therefore a new type of beam transformer has been developed using the principle of a Cryogenic Current Comparator.

The paper will give an overview on the construction and the design criteria of the experimental set-up and discuss the first results of measurements.

1 INTRODUCTION

The GSI-accelerators UNILAC and SIS will be improved in the next five years so that the design intensities of the SIS (defined by the incoherent space charge limit) can be reached [1]. $2 \cdot 10^{11}$ light ions (e.g. ^{12}C, ^{16}O or ^{20}Ne) or $4 \cdot 10^{10}$ heavy ions (e.g. ^{197}Au, ^{208}Pb or ^{238}U) in the synchroton correspond to beam currents of about 300–500 mA at 1 MHz circulating frequency. Due to extraction times of 0.1–10 s the currents in the high energy beam transport system could extend to some μA.

Various detector systems were developed and built at GSI to measure extracted beam intensities starting at 10^2 particles per second (pps) [2]. Scintillators cover the region up to 10^6 pps, for higher currents ionization chambers (IC) and secondary emission monitors (SEM) are in use. But all these detector systems more or less distort the ion beam due to energy loss and particle emittance growth by scattering. In addition, SEMs and ICs are difficult to calibrate for the various ions and energies from 100 Mev/u up to 2 GeV/u.

In the region above 1 nA a non-destructive and absolutely calibratable current measurement becomes essential to control beam losses and extraction efficiences in regular intervals. 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 just reaches some μA. Therefore a much more sensitive device type was chosen – a Cryogenic Current Comparator (CCC), developed first by I. K. Harvey (National Standards Laboratory, Sydney, Australia) in 1972 for precise dc current ratios [3]. Further devices using the CCC-principle obtained resolving powers of 10 nA [4], but the stability was inadequate due to the installed RF-SQUIDs and other technical difficulties. The next chapters will show our concept to solve these problems with new techniques. The main components of the device are displayed in fig. 1.

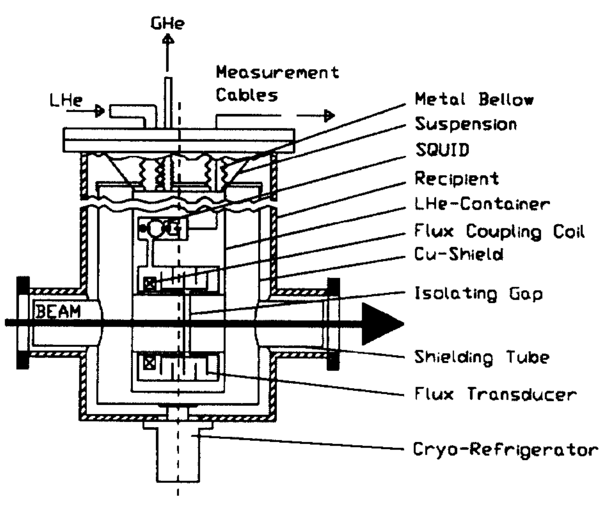

Figure 1: Design of the GSI cryogenic current comparator

2 DETECTOR SYSTEM

2.1 *CRYOSTAT*

A special bath–cryostat (fig. 2) was designed and manufactured because the passing ion beam requires a tube of 100 mm aperture. A holding time of 5–6 days shall be achieved with a stock volume of 30 l LHe. To realize this low boil-off rate the following construction features were chosen:

- the outer radiation shield is made of copper cooled by a cryo–refrigerator (T = 50 K),
- two copper shielding tubes minimize heat radiation into the "warm hole",
- the whole copper shield is wrapped up in superinsulation,
- the LHe–container is fixed with only three thin rods of titanium alloy,
- to avoid further heat conduction to the LHe–container long and thin–walled metal bellows are used and all signals are routed with thin Manganin wires.

To meet the requirements the following contributions to the heat loading of the LHe-vessel were calculated:

Heat loading of the LHe-container	Power (mW)
Conduction through titanum rods	12
Conduction through metal bellows	5
Conduction through measurement cables	51
Radiation from copper shield	26
Radiation through the "warm hole"	31
Total	125

The total heat loading of about 125 mW corresponds to a boil-off rate of 4.1 l LHe/d.

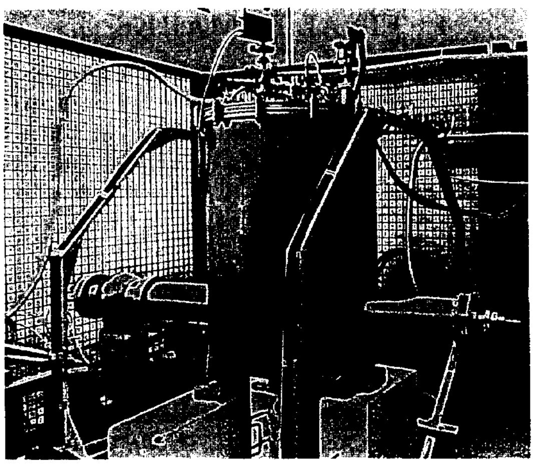

Figure 2: Cryostat with detector system
(Photo: Achim Zschau, GSI)

2.2 FLUX COUPLING SYSTEM

The flux coupling system consists of three parts: the carrier tube, the flux transducer and the flux coupling coil. To avoid the influence of wall currents an isolating gap using Al_2O_3 ceramics has been inserted into the carrier tube. Therefore only the magnetic field of the ion beam can produce a surface current in the superconducting material of the flux transducer. Due to its special geometry (gap width, inner and outer diameter) only the azimutal magnetic field component, which is proportional to the ion current, can enter the flux transducer with small attenuation, while all other field components are strongly attenuated. Calculations and measurements of various shielding cavities by the PTB in Berlin [5] showed that a folder type construction consisting of several ring cavities is easy to manifacture and achieves high attenuation factors. The following dimensions were chosen:

Inner diameter	154 mm
Outer diameter	254 mm
Gap width	0.8 mm
Number of ring cavities	4

From this we got theoretical coupling factors of nearly 0.97 for the azimutal component and only $2 \cdot 10^{-9}$ for the magnetic field component in z-direction (e.g. dipole fields). Beyond a distance of several meters to the next bending magnets, magnetic interference should be negligible.
The magnetic field of the passing current can now be transformed into a flux coupling coil consisting of a toroidal core (VITROVAC 6025-F, ®VAC GmbH, Hanau, Germany) surrounded by one winding of superconducting Niobium. This type of detector coil yields a maximum resolution, only limited by the Nyquist noise at 4.2 K of the core's loss resistance. Our calculations led to a theoretical current resolution of $\delta I_{eff} = 0.5$ nA/$\sqrt{Hz}$.

2.3 SQUID SYSTEM

The magnetic flux sensor used in this detector system is an eight-loop thin film DC SQUID in a gradiometric configuration, based on Nb-NbOx-Pb/In/Au window-type Josephson tunnel junctions. It was developed and fabricated at the Physics Department of the Friedrich Schiller University Jena. In contrast to other devices this SQUID was designed for universal applications in precision measurement technique and is working at an extremely low noise level even in an unshielded environment [6]. Measurements in a magnetically shielded room were carried out to study the noise performance of the SQUIDs. For an optimum choice of bias and flux modulation point, a white noise flux density of $2 \cdot 10^{-6}$ $\phi_0/\sqrt{Hz}$ was found. This flux noise corresponds to an equivalent current noise through the input coil of 0.9 pA/$\sqrt{Hz}$, an effective energy factor of 543 h (h: Planck's constant), and an energy resolution of $3 \cdot 10^{-31}$ J/Hz.
A point of special interest in high performance SQUID systems is the 1/f noise component. When the influence of external noise sources were suppressed by superconducting screening of the antenna only a slight increase of noise below of 100 mHz could be observed. Therefore this noise-limited sensitivity exceeds the sensitivity of the magnetic flux detector needed for the CCC for low intensity ion beams by at least one order of magnitude.
A superconducting ring core transformer is used in order to match the high inductance of the antenna (L = 40 μH) to the input inductance of the SQUID (L = 0.8 μH).

3 RESULTS OF MEASUREMENTS

3.1 CRYOGENIC PERFORMANCE

Several steps are necessary to cool down the cryostat and to fill in liquid Helium. Because the LHe-container including the detector system weighs about 100 kg this process takes three days. Continuous measurements of the Helium level yield a boil-off rate of 5.6 l LHe/d. This corresponds to a heat loading of the LHe-vessel of 170 mW and is in good agreement with the calculations.

3.2 CURRENT RESOLUTION AND NOISE LIMITATIONS

To simulate the ion beam a simple wire loop (one winding) around the flux transducer was installed. Using a picoampere current source (KEITHLEY 261) the current sensitivity of the detector system was determined to 175 nA/ϕ_0 (1 ϕ_0 corresponds to 2.5 V in the most sensitive range of the SQUID system). Fig. 3 shows a test pulse of 10 nA. The signal also indicates a slight zero drift in the order of

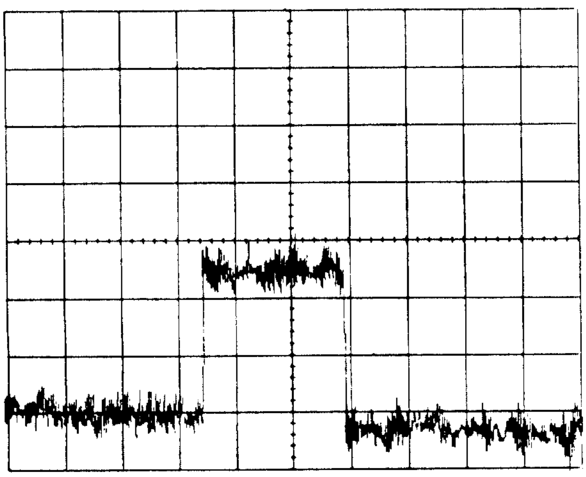

Figure 3: A 10 nA pulse, 2.5 s pulse width, taken with a bandwidth of 100 Hz (x-axis: 1 s per unit, y-axis: 50 mV per unit)

0.1 nA/s. Probably, this effect is caused by imperfectly superconducting contacts.

To determine the resolving power of the system a noise

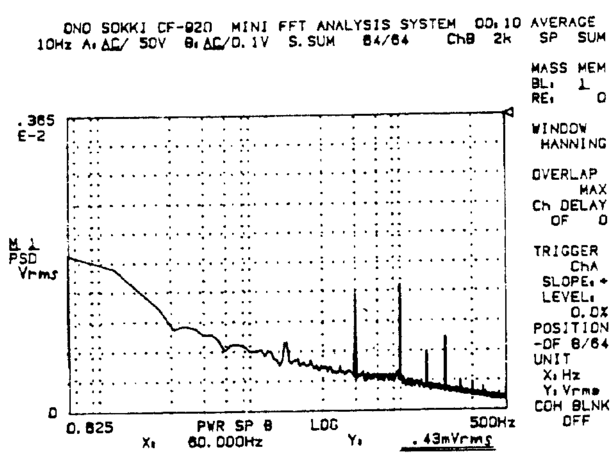

Figure 4: Noise spectrum

spectrum was taken (see fig. 4). The measured noise level of 0.43 mV_{RMS} corresponds to a current resolution of 0.24 nA/$\sqrt{Hz}$. Remarkably this value is better by a factor of 2 than the calculations. But it is known that Nyquist's noise theory is only valid for higher temperatures and supplies too small results for low temperatures.

3.3 SHIELDING EFFICIENCY

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 higher (1–2 orders of magnitude) than expected but small enough to do not prevent further tests. To get hints for constructive improvements additional calculations are necessary to explain the detected effects. They have to be minimized because the magnetic interference in the beam line will be stronger than at the test location.

4 FINAL REMARKS

On the basis of these preliminary experimental results first tests with ion beams are planned. For this purpose, the whole equipment has to be installed in a test beam line where comparative measurements with SEMs and ICs are possible. First results are expected in November 1994.

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