A non-destructive Beam Monitoring System based on an LTS-SQUID

R. Geithner, R. Neubert, W. Vodel, M. Schwickert, H. Reeg, R. von Hahn, and P. Seidel

Abstract*—Monitoring of beam currents in particle accelerators without affecting the beam guiding elements, interrupting the beam or influencing its profile is a major challenge in accelerator technology. A solution to this problem is the detection of the magnetic field generated by the moving charged particles. We present a non-destructive beam monitoring system for particle beams in accelerators based on the Cryogenic Current Comparator (CCC) principle. The CCC consists of a high-performance low-temperature dc superconducting quantum interference device (LTS DC-SQUID) system, a toroidal pick-up coil, and a meander-shaped superconducting niobium shield. This device allows the measurement of continuous as well as pulsed beam currents in the nA-range. The resolution and the frequency response of the detector strongly depend on the toroidal pick-up coil and its embedded ferromagnetic core. Investigations of both the temperature and frequency dependence of the relative permeability and the noise contribution of several nanocrystalline ferromagnetic core materials are crucial to optimize the CCC with respect to an improved signal-to-noise ratio and extended transfer bandwidth.

***Index Terms*— Accelerator measurement systems, Cryogenic Current Comparator, beam diagnostics, LTS SQUID, ferromagnetic materials**

I. INTRODUCTION

APPLICATIONS of LTS SQUIDs include precision measurement techniques in laboratory research, fundamental physics, biomedicine, and high energy physics [1].

At GSI Darmstadt an LTS SQUID based CCC detector system has demonstrated excellent capabilities for absolute measurements of the intensity of the extracted ion beam from the synchrotron. The maximum current resolution achieved with this apparatus was 250 pA/√Hz [2]. Based on these promising results new efforts were started in cooperation with GSI Darmstadt and MPI Heidelberg to develop an improved CCC for the upcoming FAIR (Facility for Antiproton and Ion Research) project [3], and for the CSR (Cryogenic Storage Ring) [4], respectively.

FAIR will be one of the leading accelerator facilities. In its final stage FAIR will consist of two fast-ramped superconducting synchrotrons SIS 100 - SIS 300, three storage rings for ion storage and associated experiments (CR, RESR, NESR), a dedicated antiproton storage ring (HESR), and the superconducting fragment separator S-FRS for the production of rare isotope beams. A unique feature of the main FAIR accelerator (SIS100) will be the generation of high brightness, high intensity primary ion beams, e.g. 3×10^{11} ions/spill of $^{238}U^{28+}$. Low intensities ($<10^9$ ions/spill) of rare isotope beams will also have to be transported by the high-energy transport beamlines [5], where installation of the CCCs is foreseen.

The CSR was developed as a novel concept for a storage ring operating below 10 K with only electrostatic ion optical devices for bending and focusing. These electrostatic devices will allow in comparison to magnetic storage rings experiments from light to rather heavy ions or molecules up to organic molecules or even biological samples. The energy of the ions will be variable between 20 to 300 keV per charge state. One aim of the CSR is the investigation of the dielectronic dissociation cross sections between molecules and electrons. For this purpose molecules in exactly defined lowest quantum states are required. Therefore, the wall temperature is set below 10 K. This low temperature reduces the black body radiation heating of the stored particles which enables the relaxation of molecules in the lowest quantum states with time constants of only 10 to 1000 s. To ensure lifetimes of 1000 s a residual gas pressure below 10^{-13} mbar (room temperature equivalent) is aspired. The cooled walls are in addition acting as cryopumps and therefore wall temperatures close to 2 K at determined positions are needed to achieve this pressure.

On the one hand non-destructive detectors outside the beam line would meet these requirements by excluding destruction of the detector due to high-intensity beams and by fulfilling the design criteria for the vacuum. On the other hand, low detection threshold and high resolutions are required to enable the detection of low-intensity beams. Secondly, a continuous monitoring of the beam currents in the accelerator beamlines requires a non-intercepting measurement method. This method must operate at a wide frequency range in order to sense currents of bunched and continuous beams, from several kHz down to DC. The cryogenic current comparator (CCC) optimally fulfills these requirements for the FAIR and the CSR beam parameters.

II. CCC CONCEPT

In the CCC, a charged particle beam current I_{BEAM}, which

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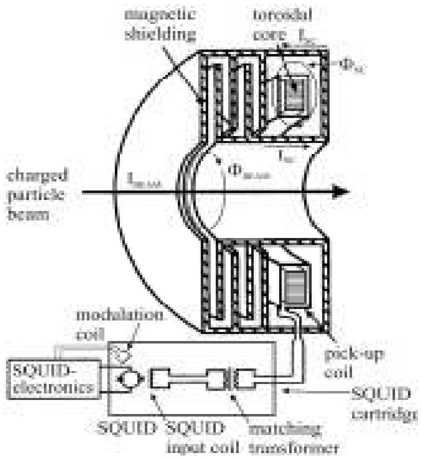

Fig. 1. Schematic diagram of the CCC. The superconducting hollow cylinder with magnetic shielding, the superconducting toroidal pick-up coil with ferromagnetic core, the superconducting matching transformer and the SQUID read-out components are all shown.

axially passes a superconducting hollow cylinder, induces screening currents I$_{SC}$ on the surface of the cylinder. A toroidal pick-up coil made of niobium with a ferromagnetic core is used to measure the magnetic field of these screening currents (see Fig. 1). The signal from the coil is fed through a superconducting transformer for impedance matching to the input coil of the readout DC SQUID.

Extensive shielding is crucial to suppress external magnetic noise which would interfere with the magnetic signal. Grohmann *et al.* [6] showed that with a number of superconducting ring cavities, any non-azimuthal magnetic field components can be reduced by several orders of magnitude. Several meander-shaped ring structures are added to the hollow cylinder design to form the magnetic shield (see Fig. 1). With our current geometry (inner radius: 69 mm, outer radius: 112 mm, number of “ring cavities”: 14, and a meander gap of 0.5 mm), we theoretically achieve a shielding factor of 200 dB for unwanted field components and only a negligible reduction of the current’s azimuthal field [7].

A key component of the CCC is the high performance DC SQUID system developed and manufactured at the Friedrich Schiller University Jena. This system makes use of the sensor UJ 111 [8], which is designed in a gradiometric configuration. An input coil system is integrated onto the chip to couple a signal into the SQUID. In most applications the SQUID works in a feedback regime at constant flux. The feedback is realized by an one turn flux modulation coil inductively coupled to one half of the SQUID loop system only.

III. NOISE LIMITATIONS AND OPTIMIZATION

Once the CCC has been successfully shielded from external noise, the DC SQUID, the shielding, and the pick-up coil must be optimized for low noise operation in order to achieve high sensitivity. With the development of LTS DC SQUIDs approaching the quantum limit, the other components of the CCC are the focus of our research. Sese *et al.* [9] have shown that for an overlapping tube type CCC, the optimal setup uses 10^5 primary windings with a matching pick-up coil and SQUID input inductance. In a CCC for ion beam measurements, the number of primary windings is fixed at one. Therefore, the sensitivity ultimately depends on the pick-up coil.

It is possible to optimize the CCC for a better noise performance by using core materials for the pick-up coil with a high permeability (μ_r) [10], as

$$B, L \propto \mu_r \Rightarrow \frac{I_s}{I_n} \propto \sqrt{\mu_r}. \qquad (1)$$

The complex permeability μ_r of the core material can be calculated from the measured serial inductance L_s and the serial resistance R_s of a toroidal coil with outer radius R_a, inner radius R_i, width b, number of windings n, as follows:

$$\mu' = \Re\{\mu_r\} = \frac{1}{n^2} \frac{2\pi}{\mu_0 b \ln R_a/R_i} \cdot L_S(f) \qquad (2)$$

$$\mu'' = \Im\{\mu_r\} = \frac{-1}{2\pi \cdot f} \frac{1}{n^2} \frac{1}{\mu_0 b \ln R_a/R_i} \cdot R_S(f) \qquad (3)$$

In a previous setup, the material Vitrovac 6025F [11] was chosen for the core of the pick-up coil due to a sufficiently high permeability at 4.2 K and an exhibited low noise level [2]. Recent developments in the area of magnetic materials with high permeability, especially the nanocrystalline materials such as Vitroperm [11] and Nanoperm [12], may permit further noise reduction [10].

An additional possibility for optimization of the overall current sensitivity is the winding ratio and the core material of the matching transformer. For a transformer the current gain in the short-circuit case only depends on the winding ratio $I_2/I_1 = n_1/n_2$.

However, the CCC with a matching transformer can be described as a series connection of two burdened transformers (see Fig. 2).

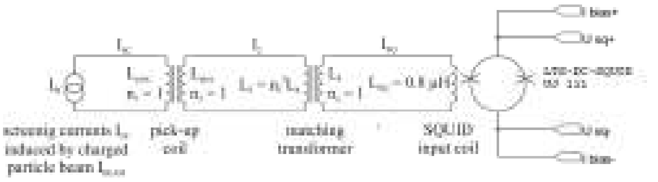

Fig. 2. Schematic circuit diagram of the CCC with pick-up coil, matching transformer, SQUID input coil and SQUID.

The ratio of the screening currents I$_{SC}$ to the current through the input coil of the SQUID I$_{SQ}$ depends on the winding ratio n$_3$/n$_4$ of the matching transformer, the inductances of the pick-up coil L$_{pick}$, the primary L$_3$ and secondary coil L$_4$ of the matching transformer, and the input coil of the SQUID L$_{SQ}$.

$$\frac{I_{SQ}}{I_{SC}} = \frac{n_3}{n_4} \cdot \frac{1}{1 + \frac{L_{SQ}}{L_4}} \cdot \frac{n_1}{n_2} \cdot \frac{1}{1 + \frac{L_3 \cdot L_{SQ}}{(L_4 + L_{SQ}) \cdot L_{pick}}} \qquad (5)$$

Setting n$_1$ = n$_2$ = n$_4$ = 1, L$_3$ = n_3^2×L$_4$, L$_{SQ}$ = 0.8 µH and L$_{pick}$ = 100 µH one can plot I$_{SQ}$/I$_{SC}$ as a function of L$_4$ and n$_3$. It can be seen in Fig. 3 that there is an optimal number of windings, n$_{3,\ opt}$ = 15, for L$_4$ = 1 µH where the current gain has a maximum of I$_{SQ}$/I$_{SC}$ = 4.1. The differences with an unburdened transformer can be seen at this point where the current gain n_3/n_4 (= 15/1) should be 15. The dependence on the inductance of the secondary coil of the matching transformer saturates for L_4 bigger than 0.8 µH which is the inductance of the input coil of the SQUID.

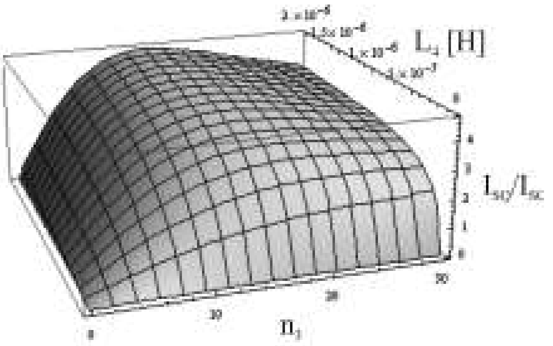

Fig.. 3. Current gain I_{SQ}/I_{SC} as a function of the inductance of the matching transformer's secondary coil, L_4, and the number of windings, n_3, of the primary coil.

The core material of the matching transformer should provide a frequency independent permeability to permit a broadband transmission and a negligible noise contribution. The amorphous Vitrovac 6030F [11] was chosen as a possible core material for the matching transformer. The magnetic properties of the abovementioned materials are well characterized at room temperature, but not at temperatures down to 4.2 K. We therefore have developed a setup to measure magnetic properties over a wide temperature and frequency range [10]. Pressure tests were carried out on selected cores because they have to endure an all-round pressure of 20 bar maximum during the warming phase of the CSR.

IV. MEASUREMENT SETUP

The materials to be tested were manufactured in the form of thin metal tapes, which were rolled to form different sized toroidal-shaped cores. The serial inductance L_s and serial resistance R_s of the samples with windings applied were measured using a commercial LCR-Bridge (Agilent E4980A). The following measurements were made at a sample temperature of 4.2 K by dipping the coils into a liquid helium dewar. Equation (2) and the known sample geometry allow the calculation of the real part µ' of the complex relative permeability μ_r.

For the noise characterization we used superconducting niobium wires as the coil windings for the different samples. The wires were connected to the input coil of a DC SQUID (UJ 111) to form a superconducting circuit. At 4.2 K the DC SQUID was used in flux-locked loop mode as a current sensor using noise optimized SQUID electronics from Jena University. The noise current of the samples were recorded with a HP 35670A spectrum analyzer. The pressure tests were carried out under helium atmosphere in a vessel. Pressures of up to 15 bar and temperatures down to 77 K could be applied throughout these tests. The serial inductance and resistance were measured before and after the test.

V. MEASURED PERMEABILITIES AND NOISE

In the application of beam current measurements varying pulse lengths requires a detection bandwidth up to at least 10 kHz. For both Vitrovac 6025F and Vitroperm 500F the permeability shows non-negligible frequency dependence in this frequency range (see Fig. 4, curve a, b).

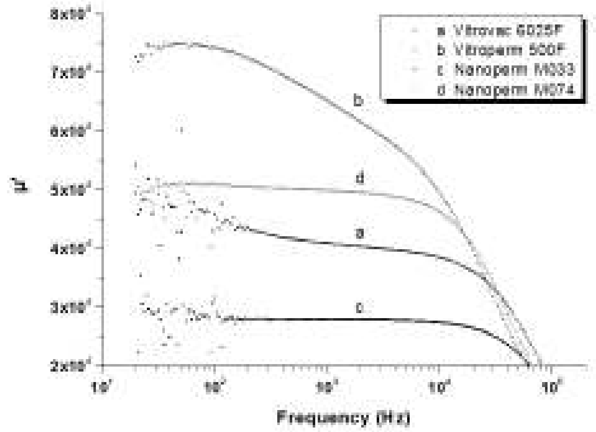

Fig. 4. Real part µ' of the relative permeability of amorphous Vitrovac 6025F and nanocrystalline Vitroperm 500F and Nanoperm M033, M074 at 4.2 K.

The frequency dependence of Nanoperm M033 and M074 showed only small variations over a wide frequency range from 30 Hz to 10 kHz (see Fig. 4, curve c, d). Nanoperm M074 even showed a higher relative permeability than the currently [2] used pick-up coil core material Vitrovac 6025F.

The losses due to material properties and additional losses due to e.g. eddy currents between the strip-wound metal tapes lead to an 1/f magnetization noise. With a superconducting pick-up coil in the CCC low frequency noise is not suppressed, which might pose a limit to the resolution at frequencies below the 1/f corner frequency [9]. To measure the magnetization noise down to 1 Hz the Vitrovac 6025F and the Nanoperm M074 sample were used with a single turn niobium coil. In a first run the SQUID noise signal with shunted input coil was measured in flux-locked-loop mode. The base noise level shows no frequency dependence down to 5 Hz (see curve c in Fig. 5).

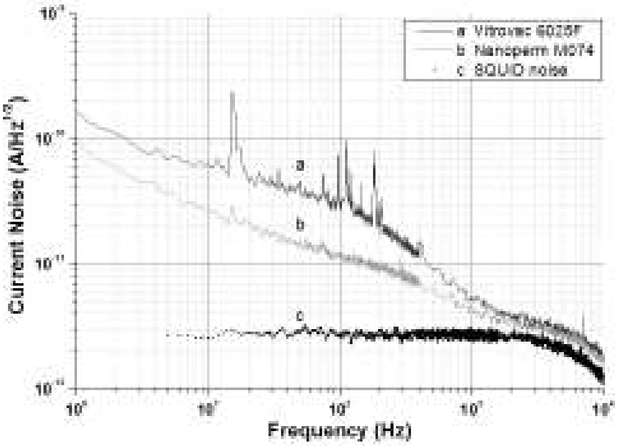

Fig. 5. The Current noise at the output of the SQUID electronics for Vitrovac 6025F (curve a) and Nanoperm M074 (curve b) cores connected to the SQUID input coil was calculated with a transfer ratio of 40×10^{-9} A/V. The dashed line (c) represents the SQUID noise level with a shunted input coil. The noise spectra were recorded with the sample and the SQUID at 4.2 K.

The measured voltage noise corresponds to a current noise of 2.9×10^{-12} A/Hz$^{1/2}$ with a transfer function of 40×10^{-9} A/V. The samples were connected to the SQUID input coil and electrically and magnetically shielded against external fields with a lead cylinder. We found that both materials had a 1/f ^{n} noise behavior with different slopes n (see Fig. 5, with n = 0.4 for Nanoperm M074). The total noise level is given by the integral over the current noise density $S_I(f)$. In the frequency range from 1 Hz to 2 kHz Nanoperm M074 has a 43 percent lower total noise (11.2×10^{-9} A, curve b in Fig. 5) than Vitrovac 6025F (19.6×10^{-9} A, curve a in Fig. 5).

The permeability of Vitrovac 6030F shows only very small variation in the frequency range from 30 Hz to 100 kHz (see Fig. 6). Unfortunately, its permeability is too small to come into consideration as core material for the pick-up coil but it fulfills the desired requirements for the matching transformer.

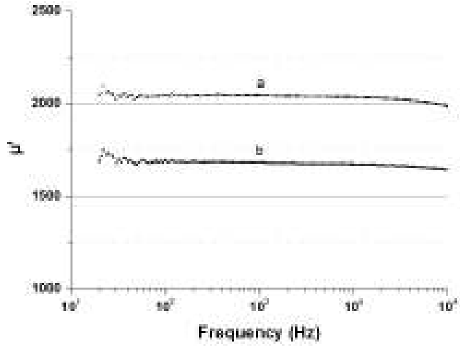

Fig. 6. Real part μ' of the relative permeability of the core material Vitrovac 6030F of the matching transformer at temperatures of 300 K (curve a) and 4.2 K (curve b).

Pressure tests were carried out on the nanocrystalline material Nanoperm M074 which is preferred as the core material for the pick-up coil. 50 copper windings were applied to measure the inductance before and after the test (see Fig. 7).

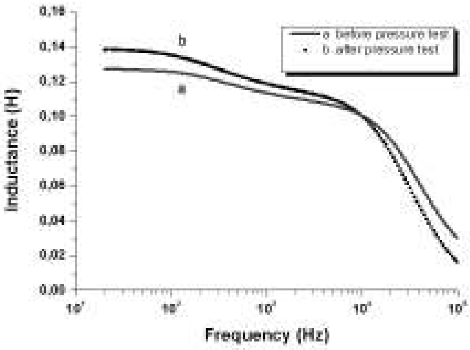

Fig. 7. Inductance of a Nanoperm M074 core with 50 copper windings measured (at 4.2 K) before (curve a) and after (curve b) the pressure test. The applied pressure of 15 bar (at 77K) was repeated 9 times.

The test was performed in a pressure vessel under helium atmosphere by increasing the pressure up to 15 bar and cooling down to 77 K. At 77 K the sample passed through 9 pressure cycles from 1 bar to 15 bar and reverse. The sample was then heated up to 300 K at 1 bar. Although the inductance has changed slightly it is not significant for this application.

VI. CONCLUSION

A SQUID-based CCC is the most sensitive device available for non-destructive low current beam measurements in a wide frequency range from DC to several kHz. To achieve a high resolution, shielding and noise isolation must be highly sophisticated. The properties of the ferromagnetic core material set the fundamental limits for noise reduction. According to our measurements nanocrystalline Nanoperm alloys provide significant advantages for the CCC due to their high permeability and low noise level at liquid helium temperatures. Through the use of this material it is possible to reduce the overall noise by more than 40 percent in the frequency range from 1 Hz to 2 kHz. Compared to [7], a current sensitivity of 11×10^{-12} A/Hz$^{1/2}$ against 40×10^{-12} A/Hz$^{1/2}$ at 100 Hz could be achieved. There are projects [13] that are working on a HTS-CCC, operating the detector with liquid nitrogen at 77 K. But, until now it has not been successful to achieve this sensitivity. The measurements presented in this article were performed on core samples with outer diameters less than 30 mm. For the CCCs at FAIR and CSR custom-made cores with much larger dimensions e.g. inner diameter of 205 mm and outer diameter of 260 mm are needed. Further measurements are planned to verify the results presented here also for samples with much larger dimensions.

REFERENCES

[1] R. L. Fagaly, “Superconducting quantum interference device instruments and applications”, *Rev. Sci. Instrum.*, vol. 77, no. 10, pp. 101101-1-101101-45, Oct. 2006.

[2] A. Peters, W. Vodel, H. Koch, R. Neubert, C. H. Schröder, Proc. of the *8th Beam Instrumentation Workshop*, Stanford, AIP Conf. Proc 451, 1998.

[3] Facility for Antiproton and Ion Research (FAIR), homepage. Available: http://www.gsi.de/fair/.

[4] R. von Hahn, J. Crespo López-Urrutia, M. Grieser, D. Orlov, C.D. Schröter, D. Schwalm, J. Ullrich, C. P. Welsch, A. Wolf, Proc. of the *European Accelerator Conference*, Lucerne, Switzerland, 2004.

[5] *An International Accelerator Facility for Beams of Ions and Antiprotons*, Conceptual Design Report, Darmstadt, 2000, Available: http://www.gsi.de/GSI-Future/cdr/.

[6] K. Grohmann, H. D. Hahlbohm, D. Hechtfischer, H. Lubbig, “Field attenuation as the underlying principle of cryo-current comparators 2. Ring cavity elements”, *Cryogenics*, vol. 16, iss. 10, pp. 601-605, Oct. 1976.

[7] W. Vodel, R. Neubert, S. Nietzsche, K. Knaack, M. Wendt, K. Wittenburg, A. Peters, "Cryogenic current comparator for absolute measurements of the dark current of superconducting cavities for TESLA", *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 743-746, June 2003.

[8] W. Vodel, K. Mäkiniemi, “An ultra low noise DC SQUID system for biomagnetic research”, *Meas. Sci. Technol.*, vol. 3, pp. 1155-1160, 1992.

[9] J. Sese, A. Camon, C. Rillo, G. Rietveld, “Ultimate current resolution of a cryogenic current comparator”, *IEEE Trans. Instrum. Meas.*, vol. 48, no. 6, pp. 1306-1313, Dec. 1999.

[10] A. Steppke, R. Geithner, S. Hechler, R. Nawrodt; R. Neubert, W. Vodel, M. Schwickert, H. Reeg, P. Seidel, “Application of LTS-SQUIDs in Nuclear Measurement Techniques”, *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 768-771, June 2009

[11] VACUUMSCHMELZE GmbH & Co. KG, Gruener Weg 37, D-63450 Hanau, Germany.

[12] MAGNETEC GmbH, Industriestrasse 7, D-63505 Langenselbold, Germany.

[13] T. Watanabe, M. Kase, Y. Sasaki, S. Watanabe, T. Ikeda, T. Kawaguchi, Y. Yano, “Current and position beam monitor with HTS SQUIDs and HTS magnetic shield for the RIKEN Ring Cyclotron”, *J. Phys.: Conf. Ser.*, vol. 43, pp. 1215-1218, 2006