OPTIMIZATION STUDIES FOR AN ADVANCED CRYOGENIC CURRENT COMPARATOR (CCC) SYSTEM FOR FAIR*

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Abstract

After successful tests with the GSI-CCC prototype, measuring beam intensities down to 2 nA at a bandwidth of 2 kHz, a new advanced Cryogenic Current Comparator system with extended geometry (CCC-XD) is under development. This system will be installed in the upcoming Cryring facility for further optimization, beam diagnostics and as an additional instrument for physics experiments. After the test phase in Cryring it is foreseen to build four additional CCC units for FAIR, where they will be installed in the HEBT lines and in the Collector Ring (CR). A universal cryostat has been designed to cope with the various boundary conditions at FAIR and at the same time to allow for uncomplicated access to the inner components. To realize this compact cryostat, the size of the superconducting magnetic shielding has to be minimized as well, without affecting its field attenuation properties. Hence detailed FEM simulations were performed to optimize the attenuation factor by variation of geometrical parameters of the shield. The beam tests results with the GSI-CCC prototype, and the developments for FAIR, as well as the results of simulation for magnetic shield optimization are presented.

INTRODUCTION

For the FAIR [1] project at GSI various new developments in the field of beam diagnostics are necessary to cover the enhanced spectrum of beam parameters. The slow extracted beams from the SIS100 synchrotron can – due to the long extraction times – have intensities which are far below the sensitivity range of regular beam transformers. For that reason it is planned to install ultrasensitive Cryogenic Current Comparators (CCC), based on superconducting SQUID technology at five locations at FAIR. With this device current measurements in the nA range have been achieved with high bandwidth (10 kHz) at GSI [2].

The CCC consists basically of a superconducting niobium torus, which represents shielding and pick-up at the same time, and a SQUID system with related electronics. The geometry and attenuation properties of the Nb torus were optimized by extensive simulation calculations. In parallel a new cryostat, enclosing the pickup and sensor unit has been developed, which fulfils the requirements at FAIR.

In addition, the analysis of spills from the FAIR synchrotrons requires a high bandwidth in combination with an excellent long term stability of the system. Since a temperature dependent baseline drift was observed during the measurements with the GSI prototype [3, 4] (as well as with the CERN/AD CCC [5]), the temperature dependence of offset and bandwidth are currently investigated in detail. Figure 1 shows the planned distribution of CCCs at FAIR.

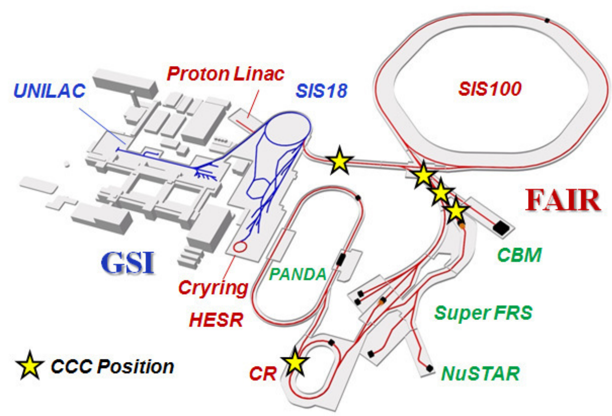

Figure 1: CCC locations at FAIR.

INTENSITY MEASUREMENTS WITH THE GSI PROTOTYPE CCC

The CCC measures the absolute beam current by detecting the beam magnetic field with a SQUID sensor, which is shielded from external fields by a pickup/shielding combination [6]. In practice the CCC voltage output is calibrated to a known current, applied through a current loop. The calibration loop is wound around the magnetic shield producing an azimuthal magnetic field which is detected by the SQUID analogue to the beam current measurement. Following that scheme, the prototype CCC measured a test current down to 4 nA with a signal to noise ratio of 6dB. The noise limited current sensitivity of the CCC installed in the beam line was calculated to 0.2 nA/√(Hz) at 1 Hz and to 2 pA/√(Hz) at 100 Hz.

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To compare the current measured by CCC with a standard technique, a Secondary Electron Monitor (SEM), installed about 1 m downstream the CCC, measured the same beam signals. During this campaign the CCC was able to measure the beam current down to 5 nA with a signal to noise ratio of 5 dB [7]. Figure 2 shows the spill structure of a slowly extracted Ni^{26+} ion beam at 600MeV extracted over 120 ms measured by both devices. It shows excellent correspondence with good time resolution.

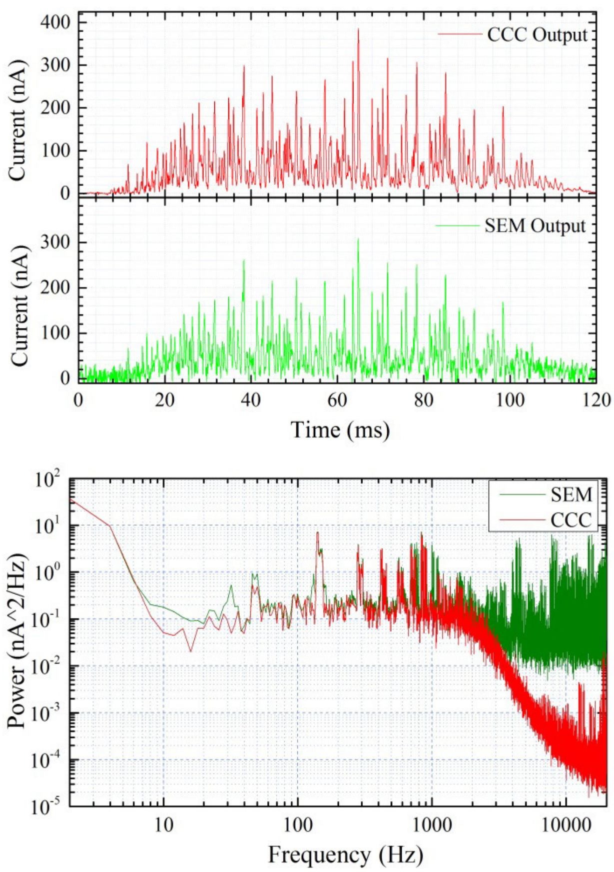

Figure 2: Upper: Comparison of the beam current signal measured by CCC and SEM. Lower: Corresponding FFT spectrum with normalized intensities and averaged over 9 spills.

From earlier investigations [8] it is known that the time structure of the extracted beam from SIS18 contains ripples caused by the magnet power converters. The FFT spectrum in figure 2 confirms that these ripples are 50 Hz and its odd harmonics as predicted. It also confirms that the CCC is the appropriate tool to study this phenomenon, since the cut-off at around 3 kHz is not visible in the SEM FFT spectrum due to background noise.

TEMPERATURE AND PRESSURE DEPENDENCE OF THE SYSTEM

The He exhaust line of the CCC bath cryostat is connected to a helium recycling system. Any fluctuations in the pressure at the exhaust of liquid helium boil-off result in temperature fluctuations inside the liquid helium cryostat. To study the influence of these fluctuations, simultaneous measurement of temperature, pressure and CCC output signal were analyzed. In case of the helium boil-off connected to the recovery line, 2.5 Hz and 5 Hz oscillations were found, which is further confirmed by the pressure sensor output. Figure 3 shows the FFT spectra of the output signals of both measurements. Here the temperature inside the liquid helium cryostat was increased by increasing the pressure (basically closing and opening the exhaust line). In parallel to the pressure measurement, a silicon diode temperature sensor installed close to the SQUID measured its working temperature.

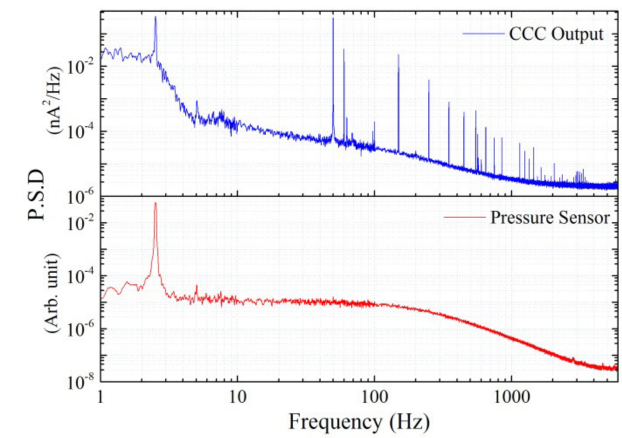

Figure 3: FFT of the output signals of CCC and pressure sensor showing the influence of pressure variation.

Figure 4 shows the CCC signal following the pressure variation up to 13 mbar, which is equivalent to a temperature variation of 32 mK. The corresponding relative current increase at the CCC output is equivalent to 650 nA.

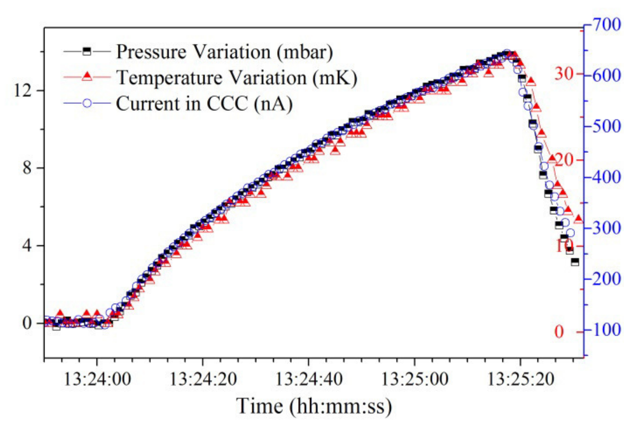

Figure 4: Time development of CCC output at variation of pressure and temperature.

Although the baseline drift does principally not affect the current resolution, it leads to the requirement of more frequent re-calibration. Therefore the measurements underline the importance of minimum thermal load as well as regulated pressure (backpressure controller) at the exhaust. Drifts during normal operation are typically more than a factor 100 smaller than shown in Fig. 4.

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OPTIMIZATION OF THE MAGNETIC SHIELD GEOMETRY

Given by the extremely low azimuthal magnetic field strength of the beam current, non-azimuthal magnetic stray fields need to be suppressed to highest possible degree. This is realized using a superconducting magnetic shield folded into a meander shaped cavity around the pickup coil. As the geometrical parameters such as the inner and outer diameters and number of meanders define the field attenuation, detailed simulations were performed using the FEM simulation package COMSOL multiphysics™ to determine the influence of these parameters on the field attenuation.

Field attenuation of an external transverse magnetic field was simulated for shields with different dimensions. Major conclusions from the simulations were: 1) the gap width (g, as shown in the Figure 1a) between the superconducting meander plates does not influence the attenuation factor; 2) field attenuation reduces as the diameter of the shield is increased as required by the larger beam tube diameter at FAIR as shown in Figure 1b. To retain the attenuation of ~ -120 dB of GSI prototype shielding (inner/outer diameter: 75/125 mm) the number of meanders had to be increased from 8 to 12 meanders in the FAIR shielding (inner/outer diameter: 125/175 mm).

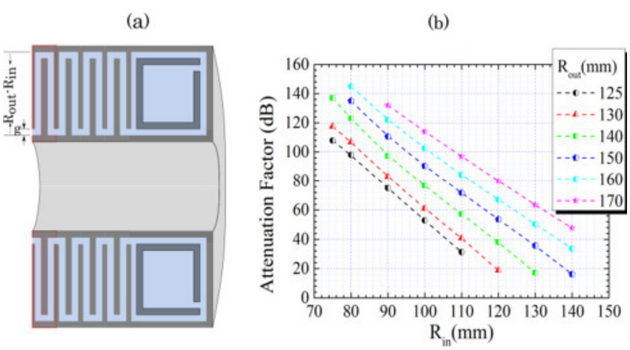

Figure 5: (a) Cross-sectional view of the magnetic shield geometry model. (b) Attenuation factor plotted for various inner and outer diameters of the magnetic shield.

THE CCC CRYOSTAT FOR FAIR

The cryostat for FAIR has to fulfill two basic requirements. 1) It has to accommodate a warm UHV beam tube 2) the beam tube must have a diameter of 150 mm. Additionally the cryostat has to provide excellent vibration damping and a good access to the CCC components without disassembling the whole structure. A design which has been worked out to match these requirements is shown in Figure 5. The isolation vacuum chamber consists of a rectangular stainless steel frame covered with O-ring sealed aluminum windows, which allow direct access to the inner components. The lower half of the front- and backside is made from steel and has a DN 250-CF contour for mounting of a big connection flange. On this flange the UHV beam tube is fixed from both sides. The beam tube itself is equipped with a ceramic gap and bellows to suppress mirror currents and vibrations. The stainless steel/aluminum tank houses a thermal shield (copper) covered by MLI, which is at the bottom of the tank connected to a refrigerator. The refrigerator shall provide the cooling down to <50 K to the shield. It is fixed with suspension wires (which also carry the thermal shield) to the top and bottom plates. The basic idea of this design is that shield and container can be lifted upwards from the vacuum tank if the UHV beam tube is removed to the side and suspensions at the bottom are released.

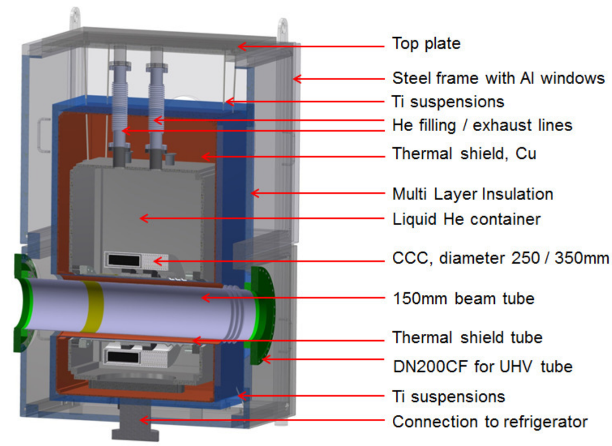

Figure 6: Schematic view of the FAIR CCC cryostat.

SUMMARY AND OUTLOOK

During beam experiments at GSI the outstanding performance of the CCC for current measurements in the nA range could be demonstrated. It was also shown that the CCC is an appropriate tool for calibration of other diagnostics devices (SEM) and for the investigation of the spill structure from a synchrotron. Concerning the temperature/pressure behaviour of the system, a strong baseline drift underlines the requirement of minimum thermal load and backpressure control.

Based on the experience with the GSI prototype, the CCC system is currently adapted to the requirements at FAIR. A magnetic shielding with enhanced dimensions has been designed by electromagnetic simulations. At the same time an advanced cryostat was developed, combining the operational requirements for FAIR with a test device for further CCC development. The FAIR CCC will be installed in Cryring@ESR in spring 2017 for test operation and ring commissioning. In this stage helium will be filled manually, tests with a He re-liquefier will take place in a second stage.

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