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OPTIMIZATION OF THE CRYOGENIC CURRENT COMPARATOR (CCC) FOR BEAM INTENSITY MEASUREMENT*

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Abstract

Triggered by the need for nA current measurement of slow extracted beams and in the storage rings at FAIR and CERN, the idea of the CCC as a current transformer has been revitalized during the last ten years. Compared to the first prototype, developed at GSI in the 90s, the second generation of CCCs is based on the possibility of detailed simulation of superconducting magnetic shielding properties, new nanocrystalline materials for the magnetic ring-cores and on superior commercially available SQUID systems. In 2014, nA resolution measurements at 2 kHz bandwidth demonstrated the possibility of spill analysis at slow extracted beams from GSI SIS18. In the following year, the first stand-alone CCC system, including a cryostat with separate He liquefier, started operation in the CERN AD. Although the existing systems show outstanding current resolution, their cost efficiency and robustness, as well as noise- and vibration sensitivity can still be improved, which is subject of ongoing research.

In this paper, recent results of our CCC tests are shown and future developments are discussed.

INTRODUCTION

Beam intensity measurement with a Cryogenic Current Comparator is based on the detection of the azimuthal magnetic field of the particle beam. This field is measured by using a pickup coil wound around a high permeability ring core which acts as a flux concentrator, an arrangement which ensures efficient coupling of the azimuthal magnetic field to the pickup. The signal from the pickup coil is fed (via a transformer for impedance matching) to a dc SQUID (Superconducting Quantum Interference Device) current sensor, which is operated in a compensation circuit, using a so called Flux Locked Loop (FLL) electronics [1]. In order to suppress disturbing magnetic noise from external fields, the pickup coil and ring core are embedded in a superconducting meander-shaped magnetic shield, providing attenuation of non-azimuthal field components of < -100 dB. Figure 1 shows the currently used arrangement, originally developed at the PTB (Physikalisch-Technische Bundesanstalt) [2].

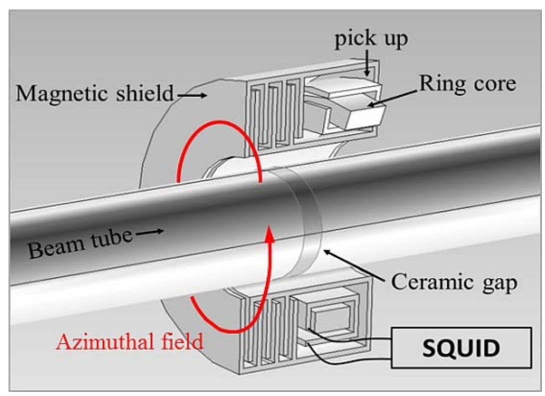

Figure 1: Principle of the CCC, shielding with radial meanders.

Following earlier work by Grohmann, Kuchnir and Peters et al. [2, 3, 4], the most recent and also most detailed investigations of the practical aspects of CCC operation in accelerators were performed in 2014 at GSI in a SIS18 extraction beamline, and in the CERN Antiproton Decelerator, where a CCC started its operation in 2015. Both systems were/are equipped with state of the art commercial SQUID systems (Magnicon© [5] and Supracon© [6] SQUIDs respectively).

While the GSI CCC basically consisted of a prior GSI prototype, equipped with a lead shielding and a VITROVAC© ring core, housed in a comparatively simple high vacuum cryostat, the AD CCC represents the first stand-alone device (including a UHV beam tube and a He reliquefier), which has been extensively optimized with respect to mechanical vibrations and slew rate limitations. For the pickup coil, a different material of the ring core was chosen, since a study at Jena University concluded that the so called NANOPERM© material had a more

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stable permeability in the given temperature and frequency range [7]. The magnetic shielding was made from Niobium. The same materials were chosen for the new CCC system for FAIR, which is currently under construction.

Both systems gave significant input for the next steps of optimization with respect to current resolution, system robustness and last but not least system costs. For illustration, Figures 2 and 3 show measurements, which have been performed with the CCC systems in the SIS18 HEBT and in the AD.

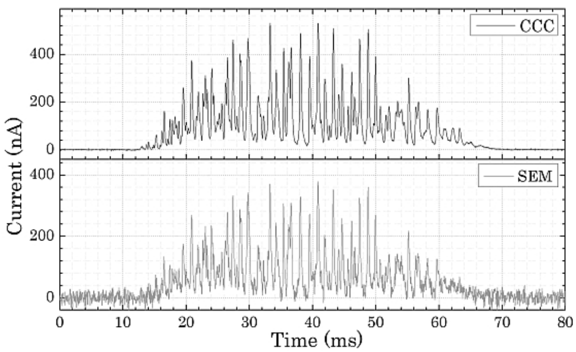

Figure 2: Spill analysis at GSI SIS18, using the CCC (upper) and a SEM foil in comparison (lower).

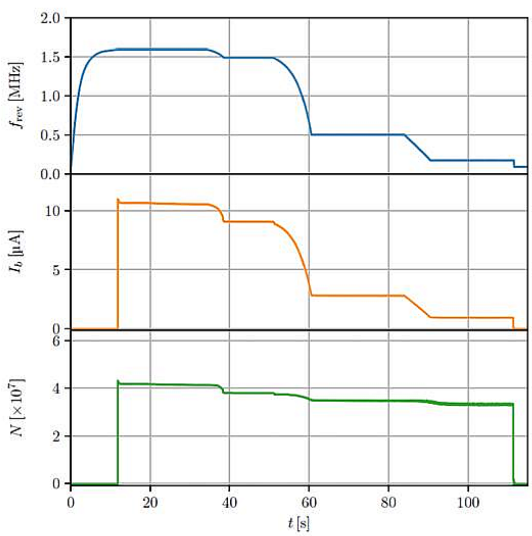

Figure 3: Deceleration cycle of the CERN AD. Revolution frequency (upper), beam intensity measured with CCC (middle) and corresponding particle numbers (lower).

SYSTEM NOISE

Figure 4 shows the input current noise spectrum of the new Nb CCC for FAIR measured in a magnetically shielded room in comparison to a twin system made of Pb. The noise figure is typical for all CCC systems showing basically three different slopes (marked in red) in the range below 1 kHz and excessive noise bursts between 10 Hz and 100 Hz. While the noise at extremely low frequencies ≤ 0.5 Hz probably derives from vibrations of the building (and underlines the necessity of best possible vibrational damping), there is some evidence that the second slope (1 Hz - 10 Hz) besides the 1/f noise is caused by the SQUID itself. However, the main subject of investigation is currently the excessive noise between 10 Hz and 100 Hz. Candidates for this contribution are microphony and/or noise in the magnetic core and mechanical vibrations of the magnetic shielding as well. Both effects are currently investigated by numerical calculations (see below). Concerning the contribution from the ring-core, tests with a coreless alternative CCC design are currently in progress to allow for comparison with the current design. Besides this work, a new shielding geometry proposed by IPHT Jena [8], as depicted in Figure 5, may improve the shielding factor and reduce the fabrication efforts.

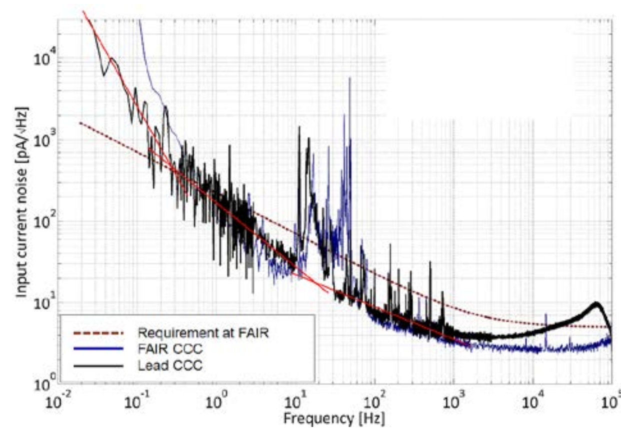

Figure 4: Noise spectrum taken from the FAIR Nb CCC in comparison to a Pb system.

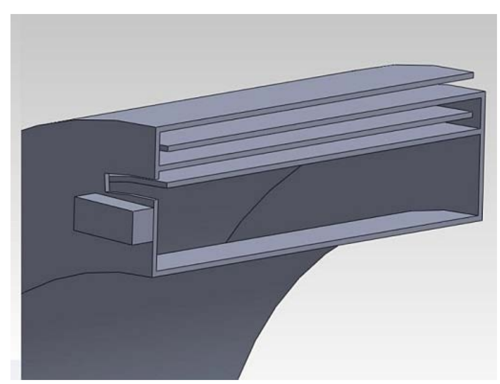

Figure 5: Alternative shielding geometry with axial meanders.

In this design, the meanders are oriented in axial direction, the SQUID is directly connected to the inner part of the shielding, which becomes therefore pickup coil and shielding at the same time. First tests look promising with respect to shielding efficiency and noise reduction below 100 Hz, but further investigations are required. Since this new pickup coil has a much smaller inductance than the former design with ferromagnetic core, it can only work effectively in connection with a new generation of low input inductance SQUID current sensors [9]. Therefore the tests are also expected to deliver valuable

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information concerning noise contribution of the SQUIDs.

Besides the intrinsic noise in Figure 4, operation in AD shows that there is also influence from well-known external sources, like mechanical vibrations of the pulsed-tube cooler and the magnetic cycles of the ring. Since these disturbances are periodic and identical, they are comparatively unproblematic and can be subtracted software-wise from the signal.

TEMPERATURE DRIFT

A significant zero drift of the CCC output in dependence on the He pressure/temperature was observed during offline campaigns at GSI and later verified in laboratory measurements at Jena and in the AD. To disentangle temperature and pressure effects, an 'anti-cryostat' was built at Jena to vary one quantity independent from the other [10]. Inductance measurements with this device could finally reduce the effect to a temperature dependence of the pickup inductance. Figure 6 shows the dependence of the inductance of a small sample of NANOPERM© cores on temperature and pressure.

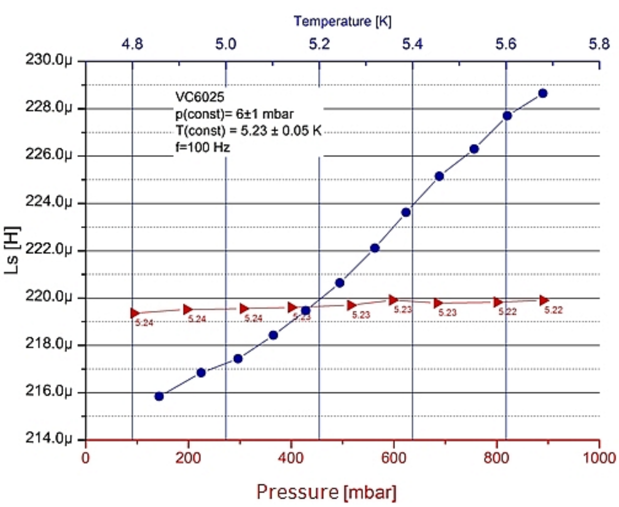

Figure 6: Inductance measurement with the 'anti-cryostat'.

The measured drifts with the CCC systems were in the range of 20 - 40 nA/mK, the effect seems to be slightly smaller for the VITROVAC© material. This is (regarding the desired nA resolution of the devices) a dramatically high value, on the other hand, the real temperature changes (within relevant time intervals) are far below 1 mK, once the cryostat has reached thermal equilibrium. Nonetheless, low frequency pressure fluctuations from recovery lines and He boil-off will have influence on long term measurements, which gives another reason for investigation of coreless CCCs.

NUMERICAL SIMUALTIONS

Numerical simulations (Comsol Multiphysics©, CST EM Studio©) have been performed in the first place to scale the attenuation factor of the GSI prototype shielding to larger CCC dimensions. This resulted in the XD-(eXtremely large Dimensions) CCC for FAIR, which has an inner/outer diameter of 250/350 mm (to cope with the 150 mm beam tubes at FAIR) and a length of 240 mm (resulting from four additional meanders, necessary to maintain the required shielding factor at the larger inner diameter) [11]. Recent calculations have been performed to compare the properties of the two competing 'radial' and 'axial' shielding geometries [12]. Since the required Nb mass and welding efforts are a significant cost-factor of the total system, the required Nb volume at a given attenuation factor has been calculated (see Figure 7). It has been shown that the shielding volume can be decreased by using 1. a large number of short meanders in the radial case; 2. a small number of long meanders in the axial case.

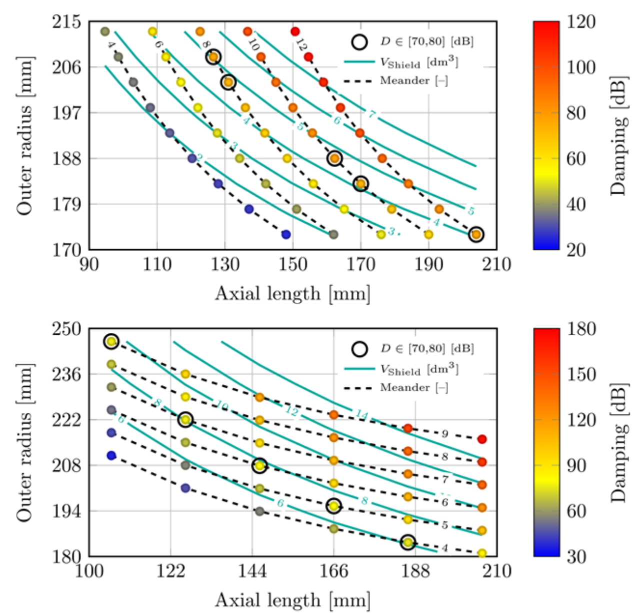

Figure 7: Niobium shielding volume for a -75 ±5 dB attenuation (encircled dots). Upper: Radial meanders. Lower: Axial meanders.

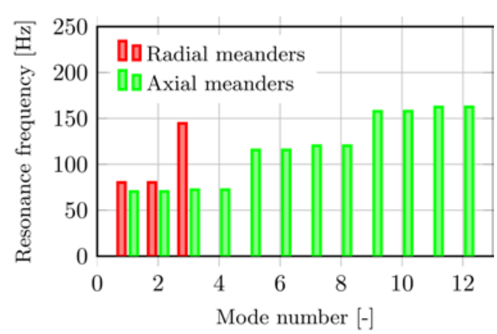

Figure 8: Mechanical eigenfrequencies of radial and axial magnetic shieldings up to 200 Hz. Both shields exhibit a -75 ±5 dB attenuation.

Using the ANSYS© software package, simulations were performed to analyze the mechanical eigenmodes of the shielding. The eigenmode spectrum shown in Figure 8 points to some of the resonances in the noise spectrum in

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Figure 4 and raises the question how the shielding itself can be designed to be more stiff - a subject which is also related to material choice.

In parallel to the analysis of the shielding, a ANSYS©-model of the FAIR CCC cryostat [13] has been developed. Figure 9 shows the mechanical design. The new cryostat will be installed in CRYRING at first, to check its cryogenics properties, to support the experimental program in CRYRING and to serve at the same time as a test bench for further CCC development. Although this cryostat will be - compared to the AD CCC - a mechanically simple system with the suspension wires of the He container fixed straight in the corners of the insulation vacuum chamber, we plan to check - and if necessary iteratively improve - its vibration behavior, avoiding mechanical resonances close to 50 Hz and higher harmonics in the final design.

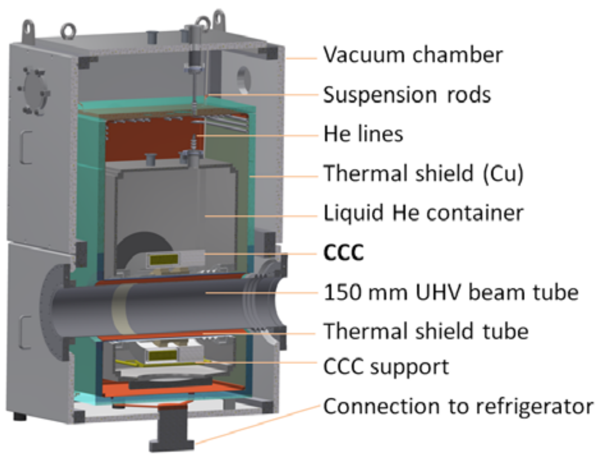

Figure 9: Design of the cryostat for the FAIR CCC.

LEAD VS NIOBIUM

The first magnetic shieldings at PTB and GSI were made from lead. Problems with the machining due to toxicity, the expectation of mechanical instability at larger dimensions and the higher critical temperature led to the choice of Nb as material for the shieldings for AD and FAIR. Recently, the discussion about materials has been relaunched - not only because of the exorbitant costs of large Nb shieldings compared to Pb, but also because Pb, as a superconductor type 1, has superior properties concerning elimination of trapped flux. Since also the problem of mechanical stability can be solved by using alloys of higher rigidity, it is planned as a next step to install a twin of the FAIR CCC made of lead in the beamline to compare the properties of the two systems.

SUMMARY AND OUTLOOK

Despite the excellent performance of the CCC in measuring currents in the nA range, there is still room for improvement of the device. Investigations are on the way covering basically all components of the CCC to reduce its intrinsic noise and to increase system robustness and cost effectiveness.

After the new CCC for FAIR has been completed and tested in the laboratory in 2017, the cryostat will be completed in mid-2018. Besides its function in the FAIR beamlines, this cryostat has been designed as a test bench for CCC development in CRYRING until the startup of FAIR. Due to its comparatively compact design and (expected) low costs, the cryostat might also be an alternative for a possible CCC in ELENA. In CRYRING, it will offer the opportunity to check the major part of the above mentioned points experimentally. In addition, there are already new proposals for further development, like CCCs with a second SQUID for reference as well as SQUID systems for enhanced dynamic range and single particle detection in resonant mode.

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