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FIRST MEASUREMENTS OF A NEW TYPE OF CORELESS CRYOGENIC CURRENT COMPARATORS (4C) FOR NON-DESTRUCTIVE INTENSITY DIAGNOSTICS OF CHARGED PARTICLES*

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Abstract

The non-destructive and highly sensitive measurement of a charged particle beam is of utmost importance for modern particle accelerator facilities. A Cryogenic Current Comparator (CCC) can be used to measure beam currents in the nA-range. Therein, charged particles passing through a superconducting toroid induce screening currents at the surface of the toroid, which are measured via Superconducting Quantum Interference Devices (SQUIDs). Classical CCC beam monitors make use of a high magnetic permeability core as a flux-concentrator for the pickup coil. The core increases the pickup inductance and thus coupling to the beam, but unfortunately also raises low-frequency noise and thermal drift. In the new concept from the Leibniz Institute of Photonic Technology the Coreless Cryogenic Current Comparator (4C) completely omits this core and instead uses highly sensitive SQUIDs featuring sub-micron cross-type Josephson tunnel junctions. Combined with a new shielding geometry a compact and comparably lightweight design has been developed, which exhibits a current sensitivity of about 6 pA/sqrt(Hz) in the white noise region and a measured shielding factor of about 134 dB.

INTRODUCTION

The accurate and non-destructive beam intensity measurement of small currents below 1 μA is a challenge. An excellent way to do this is to measure the azimuthal magnetic field of the charged particle beam and to compare that with fields of known electrical currents. Since the magnetic fields are very small, SQUIDs are used for field detection and massive superconductors for suppression of interference fields.

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History and Design

Classical CCCs for beamlines, developed in the 70s at Physikalisch-Technische Bundesanstalt (PTB) [1] and beginning in the 90s at GSI [2], have three main components: the superconductive meander structure for filtering the azimuthal field component, the pickup coil for the magnetic coupling with the SQUID, which carries out the actual current measurement and is located in the so-called SQUID cartridge (see Fig. 1).

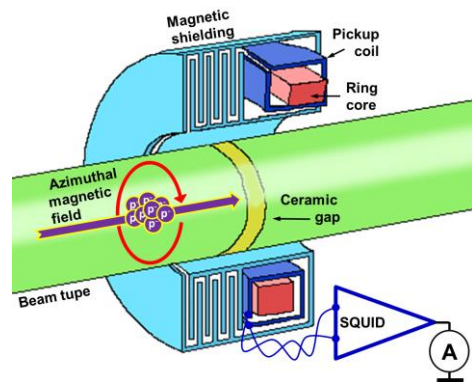


Figure 1: Classical CCC design for beamlines.

Meander Structure

The meandering structure is a shortened design of two long, coaxial superconducting tubes that realize the extraction of the azimuthal magnetic field component by shielding other components. The arrangement of the meanders was often perpendicular to the beam tube as shown in Fig. 2 (a) and called ring topology. This design has been applied to the CERN-Nb-CCC, which is currently installed at CERN-Antiproton Decelerator (AD), and to the GSI-Nb-CCC-XD, which has an inside diameter that allows it to be used on 150 mm beam tubes of the FAIR project.

Simulation shows that only long structures can provide sufficient shielding effects [3]. The production of these structures from niobium is very complex and costly. Therefore, alternatively a folded coaxial topology is possible, especially if a lot of space for the pickup coil is needed (see Fig. 2 (b) and 2 (c)). The coaxial design also facilitates the use of easy-to-process and cost-effective lead foil instead of solid niobium. A lead-foil demonstrator with a folded coaxial topology achieved an attenuation of 134 dB [4].

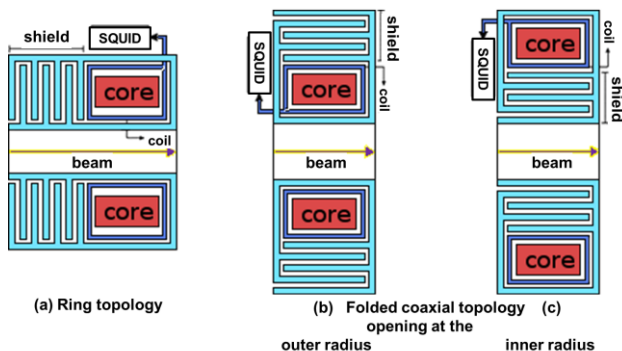


Figure 2: Meander shielding designs after [3].

Pickup Coil

Traditionally, the pickup coil is a full-wrap single turn coil around a high-permeability ring core. This core acts as a flux concentrator to make the system highly sensitive. On the other hand, the core dominates the noise and drift behaviour of the CCC. It may therefore be useful to give up the ring core and to compensate for the loss of sensitivity on the SQUID side (see Fig. 3). Such a coreless CCC (4C) was prepared at the Leibniz IPHT and measured in the Cryo Detector Lab of the University of Jena (see Fig. 4). Moreover, we did not only omit the high permeability core but we also merged the pickup coil with the folded coaxial magnetic shielding, minimizing any relative movements between both.

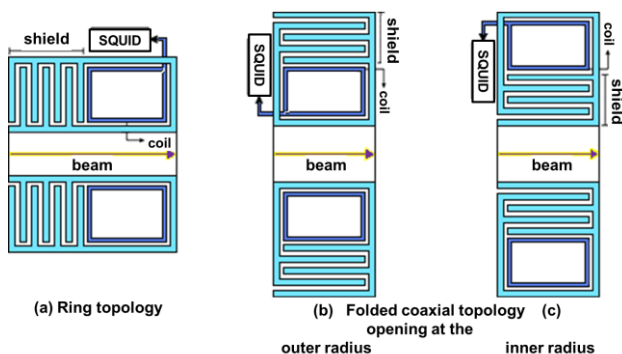


Figure 3: Meander shielding designs with pickup coils and without cores.

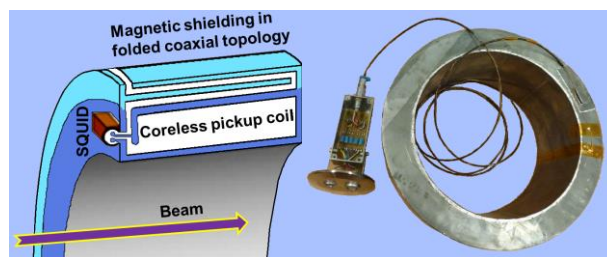


Figure 4: Pb-4C principle (left) in a folded coaxial topology and the realisation (right) with a free inner diameter of 270 mm including connection to the room-temperature filter box.

SQUID Cartridge

The classical CCC has a SQUID cartridge with the actual SQUID sensor, a possible matching transformer and possibly low-pass filter. In this case the system noise is not dominated by the SQUID noise. The core noise is at least one order of magnitude above the SQUID noise. Without the flux concentrator core, the coupling to the charged particle beam and thus the signal currents are much lower and a highly sensitive SQUID is needed. The inductivity of the pickup coil of a 4C is in the range of 10 nH, three to four orders of magnitude lower than previous versions with high permeability core. Accordingly, all parasitic inductances, like wire connection to the SQUID should be kept as low as possible, and the SQUID sensor is thus directly attached to the pickup coil.

While in a classic CCC with flux concentrator core a low-temperature SQUID does not have to be operated at its limits, for a 4C the SQUID essentially determines the system parameters. We thus make use of Leibniz-IPHT's cross-type Josephson junction technology [5], making use of submicron Josephson junctions. Their very low total junction capacitance strongly improves white flux noise and energy resolution of the devices. Specially adapted and highly sensitive SQUIDS have been developed [6] with a coupled energy resolution as low as 6 h at 4.2 K, with h being Planck's constant.

MEASUREMENTS

Prerequisite for measurements is that the magnetic shielding works properly, which means there must be no unwanted holes or short circuits. Holes allow interfering magnetic fields to penetrate, covering the actual measuring signal. Short circuits in the meander structure act as a shorted single turn and dramatically reduce signal resolution. After solving the technological problems, efficient shielding is only a matter of space available, as the effect has been studied through extensive simulations [3].

Current Pulse

The main criterion of a CCC and one of the first measurements is the proof that the system can capture defined current pulses.

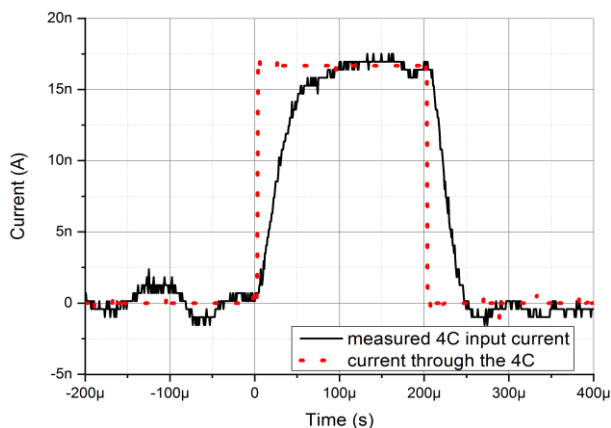


Figure 5: Single 200 μ s-17 nA current pulse measured with the IPHT-Pb-4C with 10 kHz low-pass [7].

As shown in [1] a current pulse in the range of 10 nA should not be a problem for the CCC in a laboratory environment. Figure 5 shows that it is also possible for a 4C to detect current pulses in the 10 nA range. The limited slope increase is due to the influence of a 10 kHz low-pass filter after the SQUID electronics. For the use on a storage ring - as the CRYRING with rotational frequencies in the MHz range - the high-frequency noise is not important, since it has to be averaged anyway for which e.g. at the CERN AD a 1 kHz filter is used.

Current Noise

As it was to be expected from the pulse measurements, the 4C noise is currently still somewhat above that of the CCCs with flux concentrator core (see Fig. 6). Further SQUID optimization should improve white noise (1 kHz to 100 kHz). The sensitivity to mechanical vibrations in the range between 5 Hz and 1 kHz should be counteracted constructively in the next 4C. The reason for the higher low-frequency 1/f-noise in the range 50 mHz to 1 kHz is unclear at the moment and object of further research.

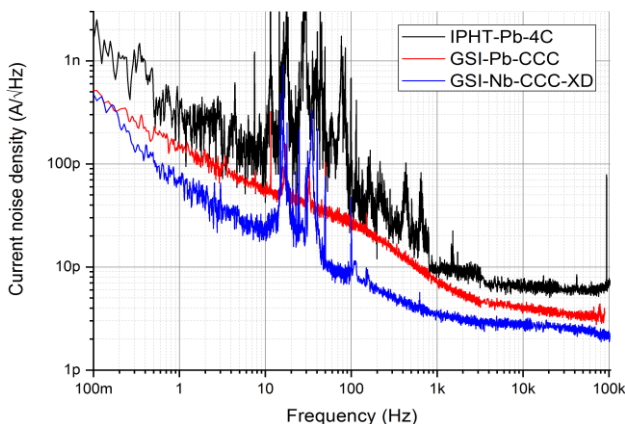


Figure 6: Comparison of the noise spectra of three CCCs. With core: Red in the middle, GSI-Pb-CCC in 2015 (4 $\text{pA}/\sqrt{\text{Hz}}$ white noise); blue at the bottom, GSI-Nb-CCC-XD in 2017 (3 $\text{pA}/\sqrt{\text{Hz}}$ white noise). Without core: Black at the top, IPHT-Pb-4C in 2019 (6 $\text{pA}/\sqrt{\text{Hz}}$ white noise).

CONCLUSION

It is possible to create a CCC without a flux concentrator core and thus to avoid negative properties of a soft magnetic core such as thermal inductance drift, frequency limitation, intrinsic magnetic fields and Barkhausen noise. In addition, the use of thin lead films can also dramatically reduce weight and cost compared to a niobium CCC of the same size.

It has been shown that an acceptable pulse resolution can be achieved. The noise measurements show that there is still development potential. The causes of the low-frequency noise should be clarified by further investigations on dry systems or with bubble-free superfluid helium-4 cooling below 2.17 Kelvin.

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