# SYSTEMATIC ANALYSIS AND MITIGATION OF DISTURBANCES IN BEAM CURRENT MEASUREMENTS USING DUAL SQUID READOUT

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*Abstract*

Cryogenic Current Comparators (CCC) with SQUID readout are planned to be used at GSI Darmstadt and the future FAIR facility (Facility for Antiproton and Ion Research) for non-invasive measurements of low-intensity ion beams. The achievable sensitivity of the device is strongly influenced by environmental disturbances, in particular mechanical and acoustic vibrations, as well as magnetic and electric interference. These disturbances can be statistical or periodic and vary over time. This work systematically investigates the signal characteristics to enable methods for the targeted suppression of periodic disturbance components. The CCC used in this work is a double-core CCC equipped with two inversely connected SQUID sensors that detect the same physical signal. Measurements with defined excitations are analysed in terms of amplitude, phase, coherence, and temporal stability. Beam signals and disturbance components exhibit different relative behaviour between the two SQUID channels, which can be exploited for disturbance suppression. Our analysis investigates methods that use phase- and amplitude-based combinations of both channels to selectively compensate variable disturbances, improving the detection of weak beam-induced signals under real conditions. Our general approach as well as first results of our filtering schemes are presented.

## INTRODUCTION

Cryogenic Current Comparators (CCC) are diagnostic devices used at GSI, CERN and the future FAIR facility for non-invasive measurements of very low beam intensities in the nA range [1]. The beam current is determined from the azimuthal magnetic field measured by a superconducting pickup coil and SQUID readout. The magnetic flux is – in case of the Dual Core CCC (DCCC) - measured by two SQUID sensors providing redundant readout [2]. In routine operation, the sensitivity of the CCC is often limited by environmental disturbances affecting the SQUID readout [3].

Although the dual-SQUID configuration inherently provides redundancy, its potential for systematic disturbance suppression has not yet been fully investigated. Previous analyses have mainly focused on averaged noise levels or specific excitation frequencies without fully characterizing the joint behaviour of both SQUID channels in time and frequency [4, 5]. A detailed understanding of the amplitude and phase relation between the channels is required to distinguish beam signals from disturbances.

Beam signals appear in both SQUID channels with nearly identical amplitudes and a phase difference of approximately 180°, whereas disturbance components exhibit different amplitude ratios and phase relations. In addition, intervals without beam signal occur between measurements, allowing disturbance components to be recorded and characterized separately.

In this work, the CCC response to defined excitation signals and idle periods is analysed. Measurements with controlled test signals are used to characterize the transfer behaviour of the two SQUID channels and to identify characteristic differences between beam signals and external disturbances. Based on these observations, several disturbance suppression schemes exploiting the redundant SQUID readout are developed and applied to spill-like measurements (beam extraction periods), with sufficient time for data processing between consecutive spills.

## EXPERIMENTAL CHARACTERIZATION OF THE CCC–SQUID SYSTEM

### *Measurement campaign and data basis*

For the analysis of the CCC system, a measurement campaign was carried out in which the responses of both SQUID channels to an injected excitation signal were recorded. Defined test signals were generated using a function generator. The generator output was converted into a proportional current by a resistor network (4.9 µA per 1 Vpp). This current is injected through a calibration wire passing through the CCC aperture. The two SQUIDs operate in an inverse configuration and therefore measure the same signal with opposite polarity [6]. All channels were sampled synchronously at 50 kSa/s using a 24-bit DT9837A data acquisition system. The system was excited using continuous logarithmic frequency sweeps from 0.1 Hz to 10 kHz over a duration of 120 s, with exponential frequency progression. In addition, measurement intervals without injected excitation were recorded to capture environmental disturbances. Furthermore, synthetic spill-like excitation signals were generated and injected through the CCC calibration input to emulate beam extraction periods. The signals consisted of finite-duration spill patterns with amplitudes in the mV range and reproducible temporal structures. Their spectral content contained dominant low-frequency components together with additional spectral structures extending into the kHz range. These synthetic excitations were used as reproducible beam-like reference signals during the measurements.

### *Amplitude and phase response of the SQUID channels*

To characterize the frequency response of the CCC–SQUID system, the input and output signals recorded during logarithmic sweep excitation were analysed. The investigated system includes the magnetic CCC and SQUID electronics. For each channel, the experimental frequency response was determined from the ratio of the injected excitation signal and the measured SQUID output. For a compact representation, the measured response in the range from 1 Hz to 10 kHz was approximated by a discrete second-order transfer function. The parameters of this transfer function were identified by fitting the frequency response to the measurement data using a weighted least-squares approach in the frequency domain. The resulting transfer functions $H_1(z)$ and $H_2(z)$ model the transfer behaviour of the two SQUID channels. Both channels exhibit similar magnitude responses, while the relative phase between them remains approximately constant at about 180° (Fig. 1). This reflects the inverse SQUID configuration. Deviations from the ideal ∼ 180° phase relation in Fig. 1(b) mainly originate from superimposed narrowband disturbance components, as these spectral lines are also present in measurements without injected excitation.

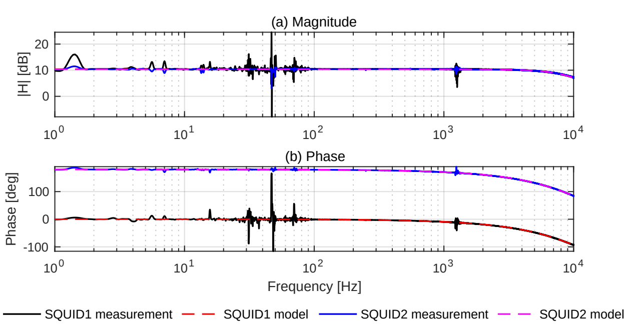


Figure 1: (a) Magnitude response and (b) phase response over the investigated frequency range. Solid lines show the measured transfer functions, while dashed lines represent the fitted digital models.

Since all identified poles lie inside the unit circle, the system can be described by a linear time-invariant model within the investigated frequency and amplitude range. This model serves as a reference for disturbance analysis.

### *Characteristics of external disturbances*

Disturbance components exhibit a different relative behaviour between the two SQUID channels compared to beam signals. While beam signals appear with nearly identical amplitudes and a phase difference of approximately 180°, disturbance components show frequency-dependent amplitude ratios and phase shifts. In the investigated system, disturbance contributions are consistently stronger in one of the SQUID channels. This behaviour is also observed in idle measurements without injected excitation, where spectral components appear in both channels with varying amplitudes and phases. The temporal behaviour of these disturbances was investigated using extended idle measurements. The data were evaluated in overlapping time windows, narrowband spectral lines were identified as local maxima and have been tracked over time. For each component, the amplitude and relative channel behaviour were evaluated. Figure 2 shows an example of the temporal evolution and the relative channel behaviour for selected spectral components.

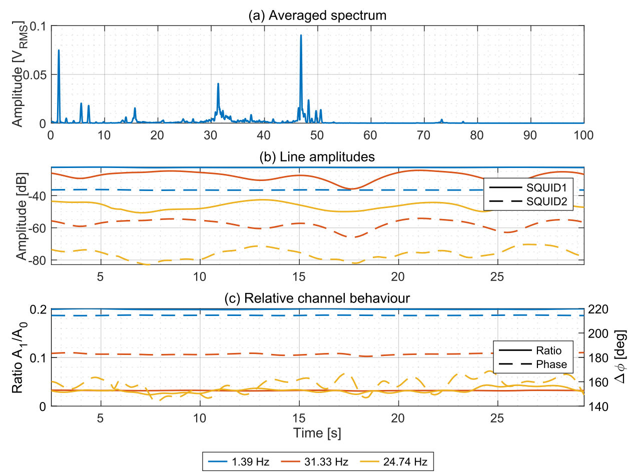


Figure 2: Temporal behaviour of selected disturbance components observed during idle measurements.

The analysis reveals both stationary and time-varying disturbance components. Some spectral lines remain stable over the entire measurement duration, with amplitude variations typically below 1 dB (1.4 Hz). Others exhibit significant amplitude variations of several decibels, while their frequencies remain approximately constant. In some cases, small frequency variations on the order of a few tenths of a hertz can be observed over longer time intervals. An example is a component around 31 Hz, indicating interference originating from time-varying external sources. In some cases, amplitude variations occur while the relative behaviour between the SQUID channels remains nearly constant, indicating unchanged coupling mechanisms. In other cases, variations are observed in both amplitude and inter-channel relation (e.g. around 25 Hz), indicating changing coupling conditions or superposition of multiple disturbance sources. Overall, the disturbance spectrum consists of stationary and time-varying components.

## DISTURBANCE SUPPRESSION STRATEGIES

The disturbance analysis described above forms the basis for several suppression strategies. Three disturbance suppression approaches were investigated: 1. notch filtering of stable disturbance lines and parametric subtraction of coherent disturbance components, 2. phase-based spectral masking exploiting the inter-channel phase relation and

3. cancellation of correlated disturbances using the relative channel response. Narrowband disturbance components were attenuated using notch filters whose frequencies were identified from idle spectra. As an alternative, coherent disturbance lines were modelled as sinusoidal components during idle intervals and subtracted from the measurement data. In addition, the relative phase behaviour between the two SQUID channels was used as a selection criterion. Frequency components whose phase deviation exceeded a tolerance around the characteristic 180° beam-signal signature were suppressed. Finally, correlated disturbances were reduced by subtracting a scaled reference component derived from the second SQUID channel.

## RESULTS

In the following, the combined application of selected suppression methods is demonstrated to illustrate the general effectiveness of the proposed disturbance mitigation strategy. Figure 3 shows the time-domain signals for the generator reference, the measured SQUID signal before processing, and the resulting signal after disturbance suppression.

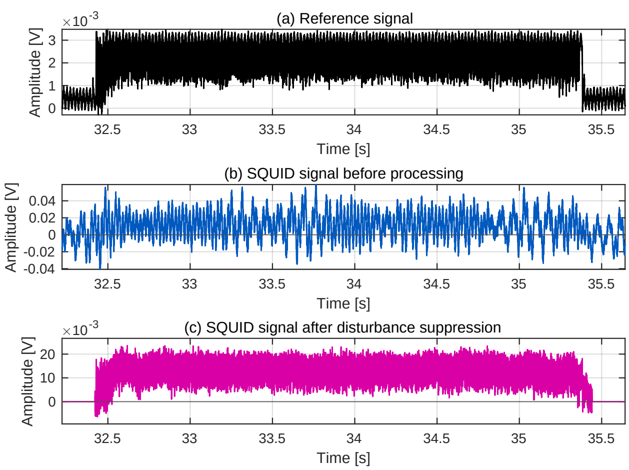


Figure 3: Time-domain signals of the reference and SQUID channels during a spill interval.

The test signal was operated in a periodic mode. Each cycle consisted of 10 s without excitation (idle phase) followed by 3 s of signal operation (spill). This sequence was repeated throughout the measurement. Idle intervals were used to characterize disturbances, while spill intervals were used to apply the suppression methods. For the analysis, one idle interval was used as a learning window. During this period, stable low-frequency disturbance components at 1.4 Hz and their harmonics were identified and modelled. The estimated components were subsequently subtracted from both the learning interval and the following spill interval. Based on the cleaned signals, the frequency-dependent relative behaviour between the two SQUID channels was determined from the idle data and applied to the subsequent spill interval. A frequency-dependent reference component was derived from one channel and subtracted from the other to reduce correlated disturbance contributions. In addition, a phase-based selection in the frequency domain was applied. Frequency components within a narrow tolerance band around the characteristic ~180° inter-channel phase relation were retained, while components with larger deviations were suppressed as disturbance-dominated. A tolerance of ±1° was used in the present implementation to reduce disturbances while preserving coherent spill-related components. This criterion relies solely on the relative phase relation between the channels. In the raw signal, pronounced periodic disturbances are visible during the idle intervals. After processing, these components are significantly reduced, while the injected spill signal is largely preserved. Short idle sections before and after the spill are shown for reference. The processed signal is normalized to the mean value of the idle sections, which defines the zero-level shown in the figure.

## CONCLUSION

The disturbance behaviour of a dual-SQUID CCC system was systematically investigated using controlled excitation signals and idle measurements. The analysis showed that beam signals exhibit a characteristic inter-channel behaviour with nearly identical amplitudes and a phase difference of approximately 180°, whereas external disturbances display frequency-dependent amplitude ratios and phase relations. Based on these observations, several disturbance suppression strategies were developed that exploit the redundant SQUID readout. The combined application of disturbance modelling, inter-channel subtraction, and phase-based spectral selection enables a significant reduction of periodic disturbance components while preserving the beam-induced signal. These results demonstrate that the dual-SQUID configuration provides a suitable basis for disturbance mitigation in accelerator operation and is compatible with real-time implementations, e.g. within a FESA-based control environment. Future work will focus on a systematic evaluation of the individual suppression methods and their performance during real beam operation.

## REFERENCES


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