Highly scalable readout electronics for large multi-channel dc-SQUID systems

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Abstract. SQUID instruments for biomagnetic diagnostics, radiometry and astrophysics are often equipped with a large number of devices. For systems with more than a few tens of sensors, read-out with an equivalent number of independent components is not an appropriate solution to meet both, technical and financial requirements. In such cases, specifically tailored readout electronics are typically used. In this presentation, the general concept of a new highly scalable and flexible electronics is presented which is intended for operation of up to several 1000 SQUID channels in the linearizing flux locked loop mode. A prototype version of the electronics for the readout of a low-noise biomagnetic system involving 72 SQUID sensors is demonstrated. Measurement results regarding gain, bandwidth, noise, and power consumption will be presented. Finally, we discuss other potential applications in magnetometry and radiation detection with transition edge sensors or metallic magnetic calorimeters.

1. Introduction

SQUID instruments designed for use in biomagnetic diagnostics [1][2][3], radiometry, or astrophysics [4] are often characterized by a high number of superconducting sensors. In these systems, the SQUID can be an integrated magnetometer, or a current sensor for readout of another superconducting sensor like a detector coil, a cryogenic calorimeter based on superconducting phase transition thermometer (SPT) or a metallic magnetic calorimeter (MMC). Independent of the specific sensor configuration, the read-out with an equivalent number of independent electronics is not a practicable solution to meet both the technical and financial requirements.

To overcome these limitations and to respond to the demands of the growing market, we have developed novel highly scalable and flexible electronics, that allows the operation of up to several 1000 dc-SQUID channels in the linearizing flux locked loop (FLL) mode.

2. Concept

The general concept of our multi-channel flux locked loop (MCFLL) electronics is based on the idea to create electronics that cover the largest number of research applications possible. This involves experimental setups in extremely magnetically shielded environments like magnetoencephalography, magnetorelaxometry or ultra-low-field nuclear magnetic resonance experiments (ULF NMR) as well as...
systems in harsh laboratory environments as typically used in the field of dark matter research. The second goal is to make the electronics as scalable as possible, i.e. to make them suitable for medium-sized measurement setups with a few tens of sensor channels as well as for ultra large systems equipped with thousands of channels.

2.1. General concept

Due to the requirements for maximum flexibility and minimum thermal impact to the experiment, the MCFLL electronics are generally not mounted on top of the cryostat—in contrast to the earlier SQUID readout by PTB [5]. Customer-specific, well shielded cables connect the highly sensitive SQUID signals to the inputs of the electronics, which are housed in 19-inch cases. Thereby, one cable contains 9 differential pairs for the voltage signal, the second cable the 9 differential pairs for the magnetic flux. A third cable is needed in case of a two-stage readout (see chapter 2.2) only.

Each 19-inch case contains 14 slots, whereby up to 13 slots can be used for MCFLL electronics leaving one slot free for the interface board. Each slot can hold one MCFLL plug-in motherboard with the dimensions of a double Eurocard (233 mm x 160 mm) to host up to 9 MCFLL electronics channels as depicted in Figure 1. Thus, one 19-inch case can host electronics for up to 117 sensor channels. In case the total number of sensor channels exceeds 117, multiple 19-inch cases are cascaded via RS-485. Each 19-inch case requires a separate power supply which is housed in an additional 19-inch case.

Figure 1. MCFLL plug-in motherboard equipped with 9 MCFLL electronics channels. For maximum flexibility, the electronics for each sensor channel are located on a separate PCB and can be plugged to the MCFLL motherboard.
2.2. FLL electronics

The key component of the measuring system is the MCFLL electronic dedicated to one sensor channel (Figure 2). Here, it is important to come up with a good compromise between high performance, low power consumption and price per channel. For this reason, MCFLL electronics have been designed for a white voltage noise level of 0.7 nV/Hz$^{1/2}$ and a maximum bandwidth of about 5 MHz (Figure 3).

![Figure 2. MCFLL electronic of a single sensor channel with the board dimensions of 24.5 mm x 100 mm.](image)

The basic design follows the well-known principle of FLL electronics which are intended to be used for readout of dc-SQUIDs [6], i.e. the MCFLL electronic basically consist of a low-noise preamplifier, an integrator and a feedback circuitry. To meet the requirements of a multi-channel instrument, the MCFLL electronics are designed for differential output, i.e. the output voltage is measured between the output FOUT and the complementary output COUT. The voltage range of each output is ±5 V.

Generally, a dc-SQUID sensor is adjusted by dc voltage, current and flux bias. In digitally controlled electronics, the bias is usually generated with the help of a microcontroller, a digital-to-analog converter (DAC), and a low-noise voltage reference—the latter determines the maximum range. To increase the number of potential applications, each MCFLL electronic channel offers 6 bias DACs. Three of them are generally used as described above. Two additional bias DACs are intended to be used for so-called two-stage readout [6], i.e. if the SQUID sensor signal is pre-amplified by a SQUID current sensor. An auxiliary bias DAC is implemented for customized applications. It can be used e.g. for modulation of the critical current of a current limiter above which the input circuit becomes normal conducting. DACs with 16 bit-resolution are chosen to allow a precise biasing.

For gain variation, the feedback circuitry is equipped with four different feedback resistors and switches, allowing parallel operation in 15 combinations. The current feedback resistor values (1.6 kΩ, 7.5 kΩ, 22 kΩ and 43 kΩ) enable feedback current in the range between ±0.1 mA and 0.3 mA. Since
high quality resistors with a typical tolerance of 0.1 % are employed, the MCFLL electronics operates with high accuracy as depicted in Figure 4.

Figure 4. Output voltage $V_{\text{out}}$ versus feedback resistance $R_f$ measured with a 24-bit resolution data acquisition device from National Instruments. A constant signal current $I_s \approx 216 \mu A$ is applied to a 10 Ω resistor which was connected to the input of the MCFLL electronics. The feedback current $I_f = V_{\text{out}}/R_f$ was calculated for the 15 resistance values and the relative deviations $\Delta I_f/I_f$ from the mean of all measurements are shown by blue squares (right scale). The standard deviation is about 0.02 %.

Each MCFLL electronic channel is equipped with a microcontroller (ATxmega256A3U), which controls the analog parts of the electronics via switches, DACs and digital potentiometers. A customer-specific data set including data of the sensor configuration, the sensor adjustment or the experimental setup, can be saved into the electrically erasable programmable read-only memory (EEPROM). The electronics always start with the values stored in the EEPROMs. Thus, a fully adjusted SQUID system can be operated without a PC, optionally controlled by auxiliary signals, which are fed via auxiliary ports (see chapter 2.3.2).

For SQUID working point adjustment, an internal generator allows modulation of each bias value (voltage, current, magnetic flux) and an additional monitor signal enables a convenient XY-display on an oscilloscope. Minimizing the number of output ports, the monitor signal of the channel under investigation is coupled to the single BNC socket which is located on the front panel of the MCFLL plug-in motherboard.

To avoid distortions generated by the microcontroller clock, the microcontroller is always set to sleep mode after each activity.

2.3. Interface plug-in board

The interface board (Figure 5) involves three circuitries: one for the data communication between PC or laptop and the MCFLL electronics, a second for power supply balancing, and a third for galvanic isolation of auxiliary signal paths which are intended to control customer-specific measurements.

As a serial interface we have chosen the RS-485 standard, which is able to drive large systems. Additionally, the RS-485 builds a half-duplex transmission system in a master-slave mode, i.e. at the same time only one device is permitted to send data whereas all the others are set to receive data. As PCs are typically equipped with a universal serial bus (USB) port, we have implemented a well-shielded, optically isolated USB to RS-485 adapter in a section of the interface plug-in board.
2.3.1. **Power balancing.** To avoid signal distortions as are typically generated by commercially available switched power supplies, the MCFLL electronics are powered via 12V-batteries. In order to generate a positive and a negative supply voltage with reference to the ground of the MCFLL electronics, a balancing circuitry has been developed, which tolerates equalizing current of up to 3 A. Since the MCFLL electronics itself are designed for maximum balancing of the supply voltages, this should be sufficient, even for fully loaded systems—the power consumption per channel depends clearly on the particular operation, whereas an averaged value of approximately 25 mA has been found.

![Image](image.png)

**Figure 5.** Interface plug-in board equipped with USB to RS-485 interface (here without shielding), with circuitry for power balancing (with heat sink), and three galvanically isolated signal paths (with BNC connector) for customer-specific measurement control.

2.3.2. **Remote control.** As describe above, the interface board provides three galvanically isolated signal paths intended for customer-specific use. These three signals are fed to each MCFLL channel for asynchronous hardware control, whereby the microcontroller can execute the same operation via software controlling, too. One signal path can be used to reset the FLL via external logic signal, which is useful e.g. in MRI experiments. The second is intended to be used for switching a SQUID current limiter, which might be integrated in the SQUID sensor design. The third is reserved for customer request and can be used as input or output, respectively.

2.4. **User interfaces and sensor data handling**

A multi-channel SQUID system generally needs specific channel information: (i) information about the electronic channel (address, specific configuration, firmware version), (ii) information about the connected SQUID sensor (sensor number, position inside the sensor module), and in most advised applications (iii) information about a superconducting sensor like a superconducting detection coil, MMC, SPT, or micromechanical device, which is connected to the SQUID sensor. Unambiguous designation and allocation are basic prerequisites for a multi-channel system and should lead to human readable documents. Furthermore, the user should be able to change entries quickly and easily—especially during test operation.
For the allocation of the components of the measuring system, MCFLL software uses initialization files, which are always based on ASCII text. The initialization file contains information about channel numbers, sensor names or sensor numbers, which is displayed in the main user interface (UI) of the software MC-SQUIDViewer after initialization.

Another MCFLL function scans a selected folder, and searches for data sheets corresponding to the sensors listed in the configuration file. Once a certain data sheet with sensor-specific parameters is found, the parameters are read and set in both soft- and hardware. Thus, various measurement or testing routines can be realized quickly by using different configuration files and data sheets.

The software MC-SQUIDViewer is always a good starting point for initialization and managing one or more selected channels. During the initializing system scan, the software searches for implemented MCFLL electronics and verifies the data communication, firmware version and operating mode of each channel. To make the time needed for the system scan as short as possible, individual channels or groups of channels can be disabled easily. Conspicuous channels are tagged after the scan and can be deactivated, which ensures system operation without distortions.

The MC-SQUIDViewer offers a variety of additional palettes, whereby the panels dedicated to verification or (re)adjustment of the selected sensor(s) are designed in colors as depicted in Figure 6.

![Figure 6. MC-SQUIDViewer with main panel for system management (white) and additional palettes for SQUID adjustment of the selected channel 0x22.](image)

### 3. First SQUID measurements

To demonstrate the technical accuracy of the concept, MCFLL electronics for the operation of about 30 channels have been built and implemented in two MCFLL demonstrator systems. One system has been equipped with two MCFLL plug-in motherboards for system-specific measurements—besides the obligatory interface plug-in. A 18-channel vector magnetometer module of PTB’s 72-channel system was chosen for the tests, which has been well characterized in the Berlin magnetically shielded room BMSR-2 [1]. Despite the 10.5 m-long cable between SQUID system, which was centered in the BMSR-2, and the MCFLL system, which was placed outside the magnetically shielded chamber, we have achieved similar noise levels (Figure 7) and far-field attenuation by implementing software gradiometers as shown in [1]. Within the MCFLL measurement system, the most sensitive channel S9
has a noise level below 200 aT/Hz\(^{1/2}\) in the frequency range above 10 kHz, and does not show a broad interference peak at around 4 kHz as discussed in [1].

![Figure 7. Spectra of SQUID magnetometers (a) oriented in x-direction and (b) of one of the most sensitive channels of PTB’s 18-channel SQUID vector magnetometer module.](image)

### 4. Conclusion

Very flexible and user-friendly dc SQUID readout electronics for linearizing FLL operation were presented. The electronics are technically state of the art and meet the requirements of multi-channel systems with thousands of channels while additional functionalities—at least partially prepared—exceed those of currently available FLL electronics. Due to the good compromise between high performance, low power consumption and price per channel, we expect to cover a large field of applications.

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