A NEW SQUID BASED MEASUREMENT TOOL FOR CHARACTERIZATION OF SUPERCONDUCTING RF CAVITIES

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Abstract

This paper presents a new system to measure very low currents in an accelerator environment, using a Cryogenic Current Comparator (CCC). In principle a CCC is a conventional current transformer using the high performance SQUID technology to sense the magnetic fields caused by the beam current. Since the system is sensitive on a pA level, it is an optimum device to detect dark currents of superconducting cavities. The system presented here is designed for the test facilities of the superconducting accelerator modules for the European XFEL at DESY in Hamburg.

INTRODUCTION

Due to the development of the TESLA technology [1] there was a large increase of the gradient of superconducting cavities. A criterion for good performance is not only the quality factor Q, but also a low rate of field emission. The field emission is the reason for the so called dark current, which consists of particles emitted by field emission, which are captured by the accelerating fields of the cavity. Since this current can be emitted at arbitrary locations in the accelerator, dark current does not fit in energy, and thus gets lost in focussing elements close to its origin. This results in additional cryogenic loss and activation of components. Therefore, dark current often is the parameter that puts practical limits to the cavity performance.

In order to develop the preparation procedures for further increase of the technically possible gradients, or guarantee a given performance during a larger production series, field emission or dark current has to be controlled during the fabrication process. The device presented here provides the necessary resolution and bandwidth to measure on the pA level. Due to the already existing cryogenic environment there is no additional complication.

The linear accelerator technology, based on superconducting L-band (1.3 GHz) cavities, is currently under study at DESY [1]. A gradient of 23.4 MV/m is required for a so-called superstructure arrangement of couples of 9-cell cavities, higher gradients are desired. The dark current, due to emission of electrons in these high gradient fields, is an unwanted particle source. Two issues are of main concern:

- Thermal load: An emitted electron from the cavity surface follows a path along the electric field lines and will most probable hit somewhere else onto the cavity wall. This leads to an additional thermal load in the cryostat, which has to be covered by the liquid helium refrigerator.
- Propagating dark current: If the energy gain is sufficient, the electrons will generate secondary particles when hitting the cavity wall which then also may generate secondaries. In the following avalanche process some electrons may pass through the iris of the cavity cell and will be further accelerated. In this case the dark current along the LINAC would grow exponentially if on average more than one electron passes the complete FODO (focus/defocus lattice) cell.

Recent studies [2] show that the second case seems to be the more critical one. It limits the acceptable dark current on the beam pipe "exit" of a TESLA 9-cell cavity to approximately 50 nA. Therefore the mass-production of high-gradient cavities with minimum field emission requires a precise, reliable measurement of the dark current in absolute values. The presented apparatus senses dark currents in the nA range. It is based on the cryogenic current comparator (CCC) principle, which includes a highly sensitive LTS SQUID as magnetic field sensor. Further on the setup contains a faraday cup and will be housed in the cryostat of the CHECHIA cavity test stand.

REQUIREMENTS FOR DARK CURRENT MEASUREMENT APPARATUS

Electrons can leave the niobium cavity material if the force of an applied external electric field is higher than the bounding forces inside the crystal structure. The highest field gradients occur at corners, spikes or other discontinuities, due to imperfections of the cavity shape. Another potential field emitter is due to any kind of imperfection on the crystal matter, like grain boundaries, inclusion of "foreign" contaminants (micro particles of e.g. In, Fe, Cr, Si, Cu) and material inhomogeneity. At these imperfections the bounding forces are reduced and electrons are emitted under the applied high electromagnetic fields [3]. With a series of special treatments the inner surface of the TESLA cavities are processed to minimize these effects. A reliable, absolute measurement of the dark current allows the comparison of different processing methods and a quality control in the future mass-production.

TESLA will be operated in a pulse mode with 5 Hz repetition rate. The 1.3 GHz r.f. pulse duration is 950 µs. During this time the dark current is present and has to be measured. Therefore a bandwidth of 10 kHz of the dark current instrument is sufficient. As field emission is a statistical process, the electrons leave the cavity on both ends of the beam pipe. Thus, half of the dark current exits at each side, and has to be measured on one side only. With the 1.3 GHz r.f. applied, we expect that the dark current has a strong amplitude modulation at this frequency. This frequency has to be carefully rejected from the instrument electronics to insure its proper operation and to avoid a malfunction of the SQUID. This were done by the help of careful r.f. shielding, appropriate filtering of all leads feeding to the SQUID input coil, and the low pass characteristic of the transformer used.

The use of a cryogenic current comparator as dark current sensor has some important advantages:

- measurement of the absolute value of the dark current,
- independence of the electron trajectories,
- accurate absolute calibration with an additional wire loop, and
- extremely high resolution.

The required working temperature of 4.2 K (boiling temperature of LHe) for the apparatus is unproblematic to provide because the CHECHIA test stand includes the whole cryogenic infrastructure for cooling the niobium cavities. In order to enable the CCC to measure the magnetic field of the dark current only, an effective shielding against external magnetic fields has to be realized.

THE CRYOGENIC CURRENT COMPARATOR (CCC)

In principle, the CCC is composed of three main components (see fig. 1):

- the superconducting pickup coil,
- the highly effective superconducting shield, and
- the high performance LTS-SQUID system.

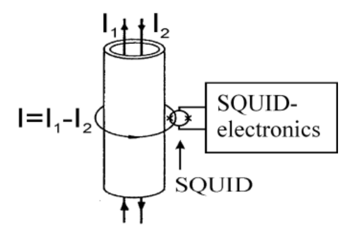

Figure 1: Scheme of a SQUID-based CCC.

The CCC, first developed by Harvey in 1972 [4], is a non-destructive method to compare two currents I_1, I_2 (see fig. 1) with high precision using a meander shaped flux transducer. Only the azimuthally magnetic field component, which is proportional to the current in the wires, will then be sensed by the pick-up coil. All other field components are strongly suppressed. The very small magnetic flux coupled into the coil is mostly detected by a SQUID.

The design of the CCC for measuring of dark currents is realized as co-operation of DESY Hamburg, Jena University and GSI Darmstadt. The apparatus will be placed in the CHECHIA cavity test stand and operates at 4.2 K.

Pickup Coil

A single turn pickup coil is formed as superconducting niobium toroid with a slot around the circumference. It contains a Vitrovac 6025-F core (Vacuumschmelze GmbH, Hanau, Germany) providing a high permeability of about 30,000 at liquid helium temperatures [5]. According to our experience 6025-F cores give the lowest noise level in comparison to other materials tested. The material inhomogeneity of the core is averaged by complete encapsulation of a toroidal niobium coil.

Superconductive Shields

The resolution of the CCC is reduced if the toroidal pickup coil operates in presence of external disturbing magnetic fields. In practice, external fields are unavoidable, therefore an extremely effective shielding has to be applied. A circular meander ("ring cavities") shielding structure (see fig. 2) allows to pass only the azimuthally magnetic field component of the dark current, while the non-azimuthal field components are strongly attenuated. The attenuation characteristics of CCC shieldings were analytically analyzed in great detail [6-8]. Applied to the shielding of the TESLA CCC an attenuation factor of approximately 120 dB for transverse, non-azimuthally magnetic field components is estimated. This result is based on the superposition of the analytic results for the different shielding substructures, here: coaxial cylinders and "ring cavities" (as shown in [9]).

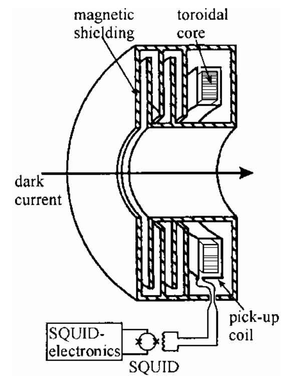

Figure 2: Schematic view of shielded toroidal pick-up coil.

SQUID Measurement System

The key component of the CCC is the high performance DC SQUID system developed and manufactured at Jena University. The SQUID sensor UJ 111 [10] is designed in a gradiometric configuration and based on Nb-NbO_x-Pb/In/Au Josephson tunnel junctions with dimensions of 3 µm×3 µm.

The SQUID electronics consists of the low noise preamplifier and the SQUID control and detector unit. The low source impedance of the SQUID (about 1 Ω) is stepped up to the optimal impedance of the preamplifier by means of a resonant transformer. The d.c. bias and flux modulation current (modulation frequency 307 kHz) are fed into the SQUID via voltage-controlled current sources situated in the preamplifier and the controller, respectively. For an optimal choice of bias and flux modulation point, a white flux spectral density of 2×10^{-6} $\Phi_0/\sqrt{Hz}$ for the SQUID system was found. This flux noise corresponds to an equivalent current noise through the input coil of 0.9 pA/√Hz, an effective energy factor of 543×h, and an energy resolution of 3.6×10^{-31} J/Hz [10].

In a DC coupled feedback loop, the field of the dark current to be measured is compensated at the SQUID by an external magnetic field generated from the attached electronics. Due to the superconductivity of all leads in the input circuitry (pick-up coil, transformer, SQUID input coil) the CCC is able to detect even DC currents. For an optimum coupling between the 1-turn toroidal pick-up coil (40 µH) and the SQUID input a matching transformer is necessary. The overall current sensitivity of the CCC was calculated to 175 nA/Φ_0.

Using a modulation frequency of 307 kHz the measurement system provides a over-all bandwidth of 20 kHz (signal level 1 Φ_0) or 70 kHz (signal level 0.1 Φ_0), respectively. Thus, it will be possible to characterize the pulse shape of the dark current beam (300 µs rise time, 950 µs flattop, 300 µs fall time, 10 Hz repetition rate) which is dominated by the r.f. structure applied to the cavities (see fig. 4).

RESULTS

Test measurements of the completed pick-up coil with all special cabling and feed throughs at 4.2 K were successfully done in a wide-neck cryostat at the cryogenic laboratory of Jena university (see fig. 3). As signal source a current generator was used to simulate the expected dark electron beam pulses. Supplying the calibration coil with a calibrated current pulse (see fig. 4, upper curve) the current sensitivity of the CCC of 200 nA/Φ_0 was found which is in a good agreement with the designed value of 175 nA/Φ_0.

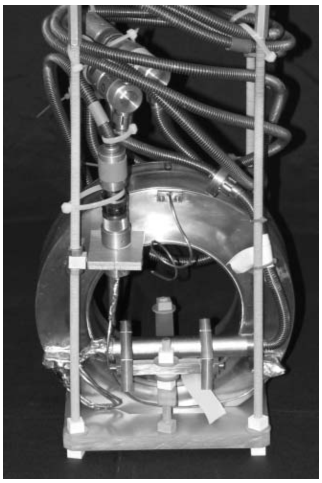

Figure 3: Nb pick-up coil prepared for tests at 4.2 K.

The flux noise of the system in the white noise region was measured to be as low as 2×10^{-4} $\Phi_0\sqrt{}$Hz (see fig. 5). These values correspond to a noise limited current resolution of the system of 40 pA/$\sqrt{}$Hz which is much better than required. As a result of the rough measurement conditions at DESY a noise limited current resolution of the CCC of 500 pA/$\sqrt{}$Hz was achieved.

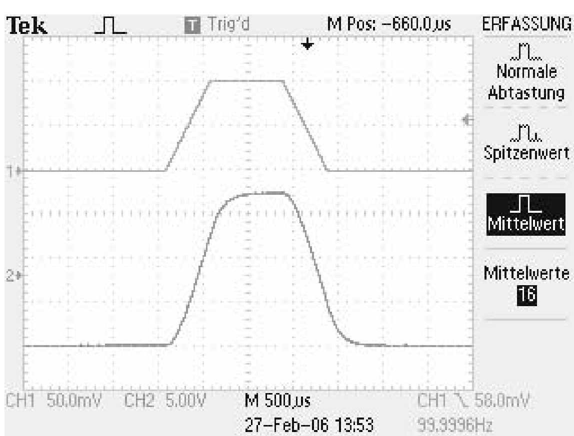

Figure 4: Current pulse test signal (upper curve) and SQUID output signal (lower curve).

Long-term measurements of the output voltage of the CCC, caused for instance by temperature drifts of the core material Vitrovac 6025-F core, showed a sufficient small drift of < 2×10^{-5} Φ_0/s.

OUTLOOK

The mechanical construction of the CHECHIA CCC is completed. Tests of the manufacturing of critical components, above all the niobium shielding and the CCC's housing, were successfully done. The SQUID electronics including special cabling and feed throughs are ready for installation at DESY.

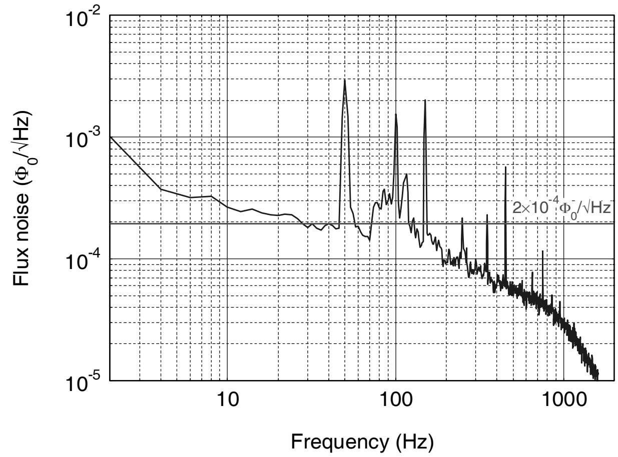

Figure 5: Noise spectrum of the CCC within a bandwidth from 1 Hz to 1600 Hz.

Measurements of the shielding factor of the CCC to compare with the calculated values will be done within the next weeks. The final installation in the CHECHIA test stand is planned during the next months.

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