SQUID BASED CRYOGENIC CURRENT COMPARATOR FOR MEASUREMENTS OF THE DARK CURRENT OF SUPERCONDUCTING CAVITIES

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Abstract

A newly high performance SQUID based measurement system for detecting dark currents, generated by superconducting cavities for the upcoming X-FEL project at DESY Hamburg, is proposed. It makes use of the Cryogenic Current Comparator principle and senses dark currents in the pA range with a measurement bandwidth of up to 70 kHz.

INTRODUCTION

The linear accelerator technology, based on superconducting L-band (1.3 GHz) cavities, is currently under study at DESY [1]. The two 10 km long main LINACs (linear accelerator) are equipped with a total of nearly 20,000 cavities. A gradient of 23.4 MV/m is required for a so-called superstructure arrangement of couples of 9-cell cavities. To meet the 2×400 GeV/c energy upgrade specifications, higher gradients of 35 MV/m are mandatory.

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 issue 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 and reliable measurement of the dark current in absolute values.

The presented apparatus senses dark currents down to a few nA. 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 (microparticles 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 and 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 is realized 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 pick-up coil,
- the highly effective superconducting shield, and
- the high performance LTS-SQUID system.

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.

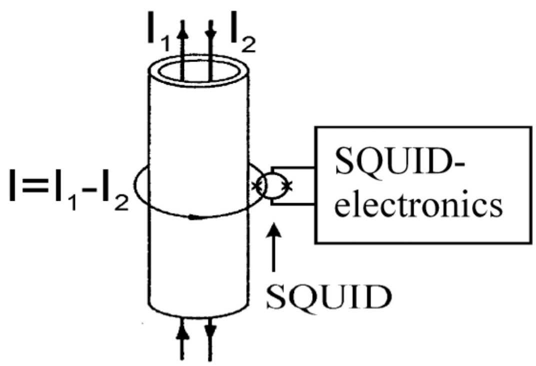

Figure 1: Simplified scheme of a LTS SQUID-based cryogenic current comparator.

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 pick-up 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. As external fields are in practice unavoidable, an extremely effective shielding has to be applied. A circular meander ("ring cavities") shielding structure (see Fig. 2) allows to pass only the azimuthal 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]).

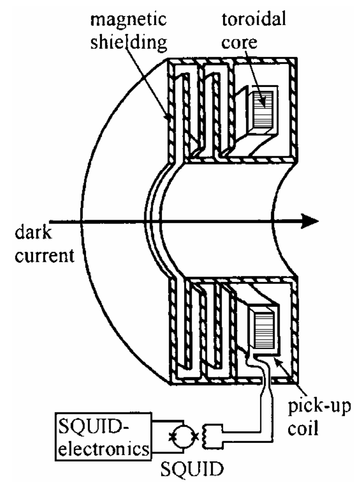

Figure 2: Simplified schematic view of the magnetic shielding, the toroidal pick-up coil, and the SQUID.

SQUID Measurement System

The key component of the CCC is a high performance DC SQUID system developed and manufactured at Jena University. The system makes use of the sensor UJ 111 [10].

The SQUID electronics consists of the low noise preamplifier and the SQUID control and detector unit. The amplification and detection of the SQUID signal is achieved by the state-of-the-art design, i.e. the preamplifier is followed by an AC amplifier and a phase sensitive detector (lock-in) with a PI-type integrator. The output signal returns via a resistor to the modulation coil to close the feedback loop.

For an optimal choice of bias and flux modulation point, a white flux spectral density of $2 \times 10^{-6}\ \Phi_0/\sqrt{\text{Hz}}$ for the SQUID system was found. This flux noise corresponds to an equivalent current noise through the input coil of 0.9 pA/$\sqrt{\text{Hz}}$.

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 coil (0.8 µH) a matching transformer is necessary.

The noise current sensitivity of the CCC was calculated to 175 nA/Φ_0. Using a modulation frequency of 307 kHz the measurement system provides an 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.

Faraday Cup

Because of the fact that the energy of dark current electrons is relatively small at CHECHIA, the design includes a Faraday Cup to have a second measurement system for comparison. The Faraday Cup will be installed at the end of the cavity vacuum chamber. The readout electronics will measure the current to ground. Also it will be needed for stopping the electrons of the dark current in the test facility. This requires a high voltage-screen to absorb the secondaries from the stopper electrode. The simplified scheme of the main component of the CHECHIA's CCC is shown in fig. 3.

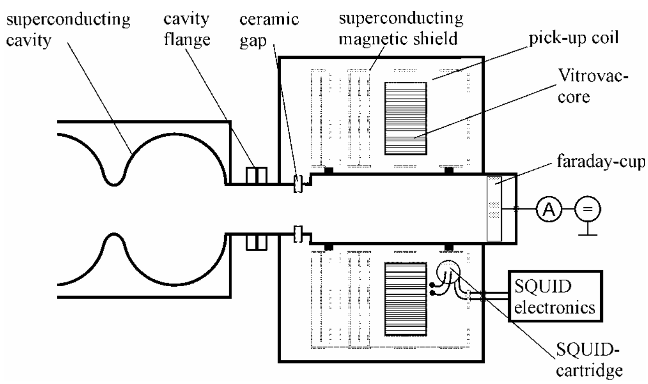

Figure 3: Schematic design of the CHECHIA's CCC.

RESULTS AND OUTLOOK

One of the most sophisticated component parts of the CCC is the superconducting pick-up coil consisting of a one turn toroidal niobium coil including an embedded VITROVAC core for impedance matching and a super-conducting meander-shaped flux transducer to attenuate the magnetic back-ground noise. This important component was manufactured successfully and tested at DESY (see fig. 4).

At 4.2 K an inductance of the pick-up coil of 40.4 µH was found which agrees quite well with the designed value. The inductances of the one turn calibration coil and the feed-back coil have nearly the same values and were determined to 42 and 40 µH, respectively.

Tests of the pick-up coil with connected SQUID system were successfully done in a wide-neck LHe cryostat. Supply-ing the calibration coil with calibrated current pulses the cur-rent sensitivity of the CCC could be measured to (202 ± 4) nA/Φ_0, rather near to the designed value (see fig. 5).

In spite of the rough measurement conditions at DESY the SQUID system worked quite well and the lowest flux noise level of $4 \times 10^{-3}\ \Phi_0/\sqrt{Hz}$ was measured in the frequency range of 30 Hz to 400 Hz. This value corresponds to a noise limited current resolution of the CCC of $0.8\ nA/\sqrt{Hz}$ (see fig. 5).

As the next step the noise limited intrinsic parameters of the SQUID based CCC and the attenuation factor against external magnetic background fields have to be measured under quiet measurement conditions.

At the end of 2005 the whole CCC will be installed in the CHECHIA test stand at DESY.

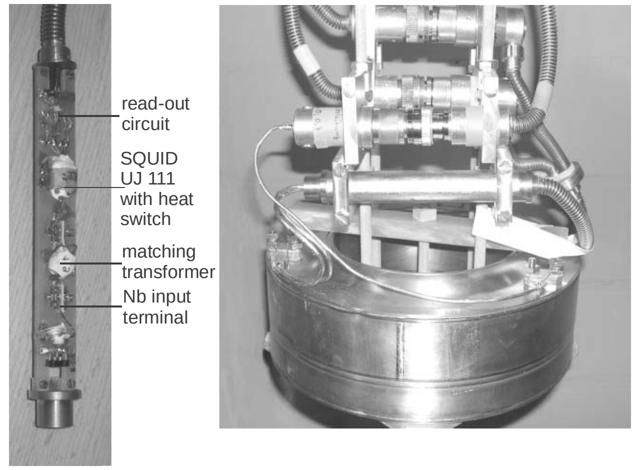

Figure 4: Cryogenic probe with LTS-SQUID (left) and completed niobium pick up coil of the CCC (diameter: 230 mm) with all special cabling for the SQUID (right).

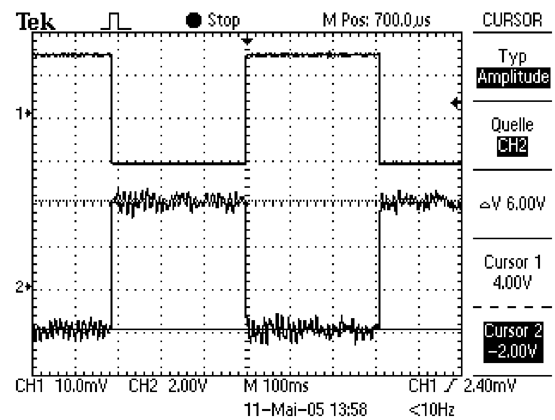

Figure 5: 126.5 nA current pulse through the calibration coil (upper curve) and corresponding 6 V SQUID output pulse (lower curve) at a system sensitivity of $10\ V/\Phi_0$.

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