HIGHLY SENSITIVE MEASUREMENTS OF THE DARK CURRENT OF SUPERCONDUCTING CAVITIES FOR TESLA USING A SQUID BASED CRYOGENIC CURRENT COMPARATOR

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Abstract

A newly high performance SQUID based measurement system for detecting dark currents, generated by superconducting cavities for the upcoming TESLA project (X-FEL) 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 2×250 GeV/c TESLA linear collider project, currently under study at DESY [1], is based on the technology of superconducting L-band (1.3 GHz) cavities. 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 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 (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, 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.

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.

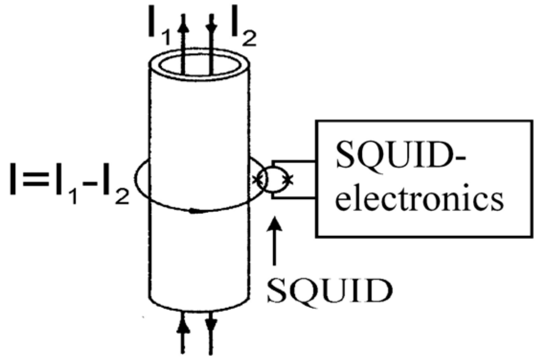

Figure 1: Simplified scheme of a LTS SQUID-based cryogenic current comparator.

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 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. 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]).

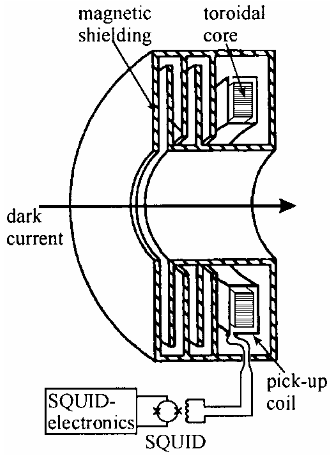

Figure 2: Simplified schematic view of the magnetic shielding, the toroidal pick-up coil, and the SQUID.

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], which is designed in a gradiometric configuration and based on Nb-NbO_x-Pb/In/Au window-type Josephson tunnel junctions with dimensions of 3 µm×3 µm. To couple a signal into the gradiometer-type SQUID an input coil system is integrated on the chip consisting of two coils of 18 turns each, connected in a gradiometric configuration. The input inductance of the SQUID is about 0.8 µH. In most applications the SQUID works in a feedback regime at constant flux. The feedback is realized by a one turn flux modulation coil inductively coupled only to one half of the SQUID loop system.

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. 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 $2\times10^{-6}\ \Phi_0/\sqrt{\text{Hz}}$ for the SQUID system was found. This flux noise corresponds to an equivalent current noise through the input coil of 0.9 pA/√Hz, an effective energy factor of 543×h, and an energy resolution of 3.6×10^{-31} J/Hz. Using optimum electric and magnetic screening of the sensor the 1/f noise knee was found below 0.1 Hz even in a normal laboratory environment [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 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.

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. We installed the faraday cup 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 components of the CHECHIA's CCC is shown in fig. 3.

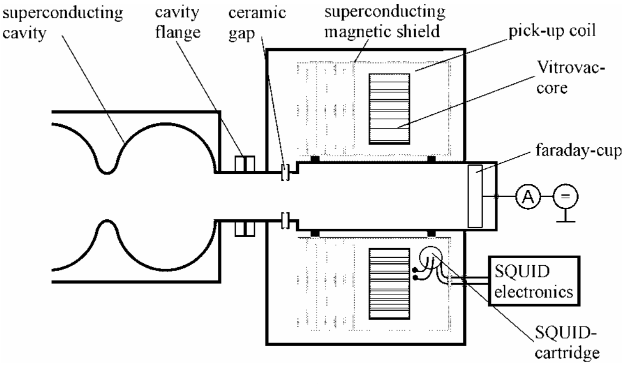

Figure 3: Schematic design of the CHECHIA's CCC.

RESULTS AND OUTLOOK

Test measurements with all special cabling and feed throughs were successfully done at the cryogenic laboratory of Jena university and a special pick-up coil to emulate the real pick-up coil under fabrication (see Fig. 4) was applied. As signal source a current generator was used to simulate the expected dark electron beam pulses.

In this test configuration a system current sensitivity of 167 nA/Φ_0 was reached using a calibration wire fed through the pick-up coil to emulate the beam. The flux noise of the system in the white noise region was measured to be as low as 8×10^{-5} Φ_0√Hz. These values correspond to a noise limited current resolution of the CCC of 13 pA/√Hz which is much better than required. According to our experience, in the final system the current resolution will be decreased by at least one order of magnitude because of the additional noise contribution due to the core material of the pick-up coil and external disturbing magnetic fields.

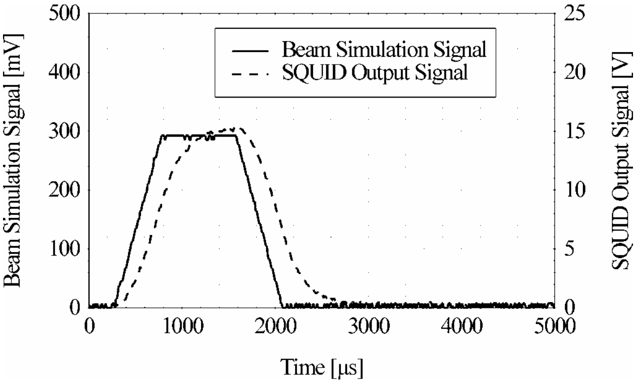

Figure 4: Test signal and SQUID output signal.

The mechanical construction of the CHECHIA CCC is completed. Tests of the manufacturing of critical components, i.e. the niobium shielding, are under way. The SQUID electronics including special cabling and feed throughs are ready for installation at DESY. The final installation is planned at the end of 2004.

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