# Cryogenic Current Comparator for Absolute Measurements of the Dark Current of Superconducting Cavities for TESLA

W. Vodel, R. Neubert, S. Nietzsche, K. Knaack, M. Wendt, K. Wittenburg, and A. Peters

*Abstract*— **A new SQUID based measurement system for detecting dark currents, generated by the TESLA (Tera Electron Volt Energy Superconducting Linear Accelerator) cavities is proposed. It makes use of the Cryogenic Current Comparator principle and senses dark currents in the nA range.**

**To reach the maximum possible energy in the TESLA project is a strong motivation to push the gradients of the superconducting cavities closer to the physical limit of 50 MV/m. The field emission of electrons (dark current) of the cavities at strong fields may limit the maximum gradient. The absolute measurement of the dark current in correlation with the gradient will give a proper value to compare and classify the cavities.**

**This contribution describes a Cryogenic Current Comparator (CCC) as an excellent tool for this purpose. The most important component of the CCC is a high performance DC SQUID system which is able to measure extremely low magnetic fields, e.g. caused by the extracted dark current. For this reason the SQUID input coil is connected across a special designed pick-up coil for the electron beam. Both the SQUID input coil and the pick-up coil form a closed superconducting loop so that the CCC is able to detect dc currents down to 1 nA/√Hz. Design issues and the application for the CHECHIA (horizontal test cryostat) cavity test stand at DESY are discussed.**

*Index Terms*—**CCC, cryogenic current comparator, SQUID, particle accelerator, TESLA.**

## I. INTRODUCTION

THE 2x250 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 MV/m is required for a so-called superstructure arrangement of couples of 9-cell cavities. To meet the 2x400 GeV/c energy upgrade specifications, higher gradients of 35 MV/m are mandatory.

Dark current, due to emission of electrons in these high gradient fields, is an unwanted particle source. Two issues are of main concern:

*1) 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 cryo-plant.

*2) 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.

## II. REQUIREMENTS OF THE DARK CURRENT INSTRUMENT

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 other material inhomogeneous. 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

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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 rf pulse duration is 800 µs. During this time the dark current is present and has to be measured. Therefore a bandwidth of 1 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 rf applied, we expect that the dark current has a strong amplitude modulation at this frequency. This frequency has to be rejected from the instrument electronics to insure its proper operation. The dark current limits and the related energy range of the electrons are shown in Table 1.

TABLE I
EXPECTED DARK CURRENT PARAMETERS

| Parameters | 9-cell test cavity in CHECHIA | TESLA cavity modules (14x9-cell cavity) |
|---|---|---|
| Energy of dark current electrons | up to 25....40 MeV | up to 350....560 MeV |
| dark current limits | < 50 nA | < 1µA |

The use of a faraday cup as dark current detector for the TESLA cavity string will suffer from the high electron energies and low currents. The capture of all secondary electrons in the stopper is challenging. The use of a cryogenic current comparator as dark current sensor has some advantages:

- measurement of the absolute value of the dark current,
- independence of the electron trajectories,
- simple calibration with a wire loop,
- high resolution,
- the electron energies are of no concern.

The required liquid He temperatures for the apparatus are of no problem, as the CHECHIA test stand includes all the cold infrastructure. Because the CCC detector measures the magnetic field of the dark current an effective shielding to external magnetic fields has to be considered.

## III. CRYOGENIC CURRENT COMPARATOR PRINCIPLE

A CCC is composed of three main components (Fig. 1):

*1) a superconducting pickup coil,*

*2) a high effective superconducting shield,* and

*3) a LTS-SQUID system.*

Principle of operation:

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 azimuthal 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. At GSI Darmstadt a CCC detector system has demonstrated its excellent capabilities for absolute measuring the intensity of the extracted ion beams from the synchrotron. The maximum resolution achieved was 250 pT/√Hz [5].

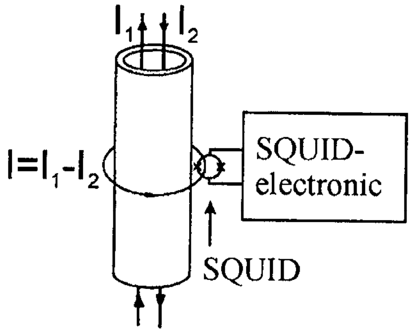

Fig. 1. Siplified scheme of a LTS SQUID-based Cryogenic Current Comparator (CCC).

## IV. THE CHECHIA CCC DESIGN

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

### *A. Pickup Coil*

A single turn pickup coil is formed as superconducting niobium toroid with a slit around the circumference. It contains a Vitrovac 6025-F core (Vacuumschmelze GmbH, Hanau, Germany), which provides low noise and high permeability even at liquid helium temperatures. The material inhomogeneity of the core are averaged by complete encapsulation of a toroidal niobium coil.

### *B. Shielding Aspects*

The resolution of the CCC is reduced, if the toriod pickup 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 (Fig. 2) allows to pass only the azimuthal magnetic field component of the dark current, while the non-azimuthal field components are strongly attenuated.

Using a superconducting shield material, like niobium, leads to an ideal diamagnetic conductor, which implies the vanishing of all normal components of the magnetic fields at the superconducting surface. The attenuation characteristics of CCC shieldings was analytically analyzed in great detail [6-8]. Applied to the shielding of the proposed TESLA CCC, with the dimensions:

| | |
|---|---|
| inner radius $r_i$: | 69.0 mm |
| outer radius $r_a$: | 112.0 mm |
| number of "ring cavities": | 14 |
| meander gap width: | 0.5 mm |

An attenuation factor of approximately 120 dB for transverse, non-azimuthal 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]).

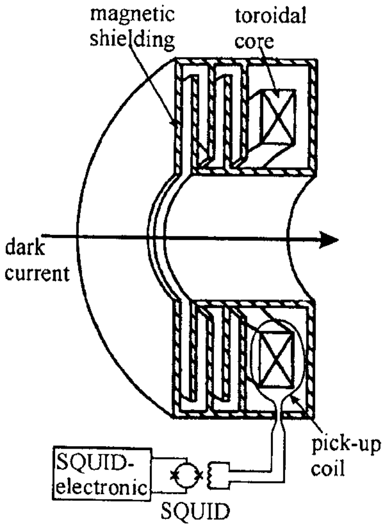

Fig. 2. Schematic view of magnetic shielding, pick-up coil and SQUID

For verification a numerical analysis was set up. To compare with the analytic computations, we first tested the numerical approach on the coaxial cylinders. A pillbox cavity was used to apply external fields of first order (magnetic dipole). In this way we could made use of the MAFIA eigenmodesolver E in simple 2D $r_z$-coordinates, analyzing the dipole modes. For a ratio $r_a/r_i = 1.1$ the analytic result of [6] could be verified to a few percent (radial components of the magnetic fields of the first eigenmode). Applying this numerical method to the actual shielding structure gives a minimum attenuation of 94 dB, which seems to be more realistic.

The same numerical method was used to study the shielding efficiency at rf. Now TM monopole modes are excited, which apply the same azimuthal fields as the dark current (Fig. 3). The attenuation through the shielding structure at frequencies > 900 MHz is very high. It is in the negligible range of 200 dB. This gives us confidence, that the strong 1.3 GHz frequency component will be suppressed sufficiently.

### C. *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 $Nb\text{-}NbO_x\text{-}Pb/In/Au$ window-type Josephson tunnel junctions with dimensions of 3 μm × 3 μm. To achieve a low total inductance the SQUID loop consists of eight sub-loops connected in parallel. 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 suitable for an optimal matching to all common signal sources. In most applications the SQUID works in a feedback regime at constant flux. The feedback is realized by an one turn flux modulation coil inductively coupled only to one half of the SQUID loop system.

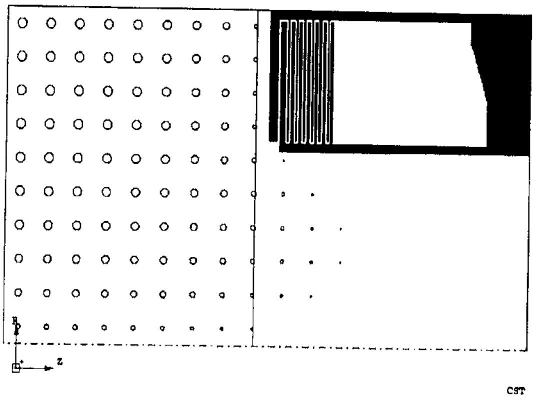

Fig. 3. Numerical analysis of the shieding with the MAFIA eigenmode solver E

In contrast to other sensors the SQUID *UJ 111* was designed for universal applications in precision measurement technique and is working at an extremely low noise level also in a magnetically unshielded environment. The long term stability of the SQUID parameters during a time period of several years is remarkable although the SQUIDs are not encapsulated hermetically. According to our experience there is no influence on the SQUID parameters caused by more than 100 cooling down cycles.

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 300 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 $2 \times 10^{-6}\ \Phi_0/\sqrt{\text{Hz}}$ for the SQUID system was found. This flux noise corresponds to an equivalent current noise through the input coil of 0.9 $\text{pA}/\sqrt{\text{Hz}}$, an effective energy factor of 543×h, and an energy resolution of $3.6 \times 10^{-31}$ J/Hz. Using optimal electric and magnetic screening of the sensor the 1/f knee was found below 0.1 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 (Fig. 4).

Both the SQUID input coil and the pickup coil form a closed superconducting loop so that the CCC is able to detect DC currents. Using a modulation frequency of 300 kHz in the complete measurement system provides a bandwidth of 20 kHz (signal level 1 $\Phi_0$) or 60 kHz (signal level 0.1 $\Phi_0$), respectively. Thus, it will be possible to characterize the pulse shape of the dark current beam, which is dominated by the rf structure (300 µs rise time, 800 µs flattop, 10 Hz repetition rate) applied to the cavities.

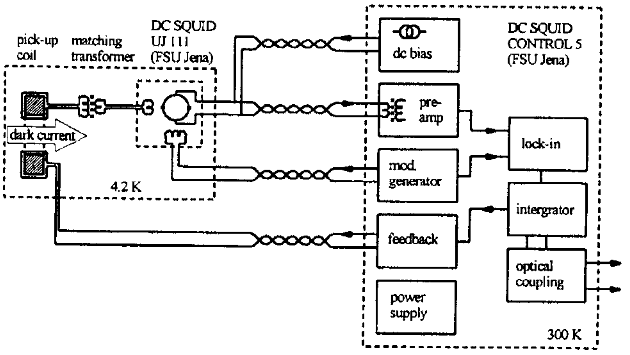

Fig. 4. Electrical scheme of the Cryogenic Current Comparator.

### D. *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 HV-screen to absorb the secondaries from the stopper electrode.

A simplified scheme of the main components of the CHECHIA's CCC is shown in fig. 5.

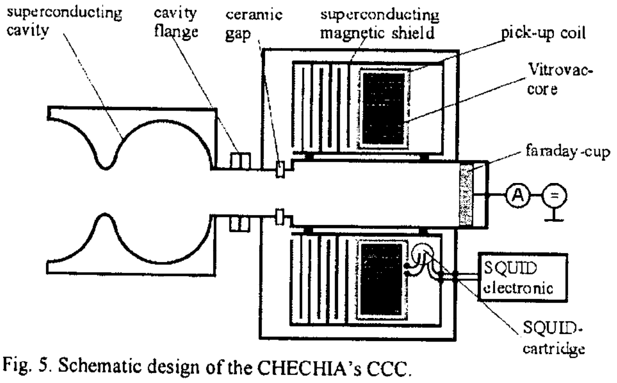

Fig. 5. Schematic design of the CHECHIA's CCC.

## V. OUTLOOK

The mechanical construction of the CHECHIA CCC is completed. Test on the manufacturing of critical components, i.e. the niobium shielding are under way. The hardware will be completed at the end of 2002. The SQUID electronics including special cabling and feedthroughs are ready for installation. The final installation is planed in spring 2003.

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