CRYOGENIC CURRENT COMPARATOR FOR ABSOLUTE MEASUREMENTS OF THE DARK CURRENT OF SUPERCONDUCTING CAVITIES FOR TESLA

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Abstract
A measurement system for detecting dark currents, generated by the TESLA cavities, is proposed. It is based on the cryogenic current comparator principle and senses dark currents down to the nA range. Design issues and the application for the CHECHIA cavity test stand are discussed.

1. 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 10.9 km long main linacs are equipped with a total of 21024 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 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, thermal load and propagating dark current [2].
Recent studies [3] 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 superconductiong field sensor (SQUID). The setup contains a faraday cup and will be housed in the cryostat of the CHECHIA cavity test stand.

2. 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 [4]. 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 rf pulse duration is 950 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 measure 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.

Parameters	9-cell test cavity in CHECHIA	TESLA cavity modules (12x9-cell cavity)
Energy of dark current electrons	up to 25....40 MeV	up to 350....560 MeV
dark current limits	< 50 nA	< 1µA

Table 1: Expected dark current parameters

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 are 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 temperature for the CCC and the cryogenic infrastructure for the whole apparatus will be provided by the CHECHIA test stand. An effective shielding to external magnetic fields has to be considered, because the CCC detector measures the magnetic field of the dark current. At GSI Darmstadt a CCC detector system has demonstrated its excellent capabilities to measure ion currents in the extraction beam line of the heavy ion synchrotron [5].

3. PRINCIPLE OF THE CRYOGENIC CURRENT COMPARATOR (CCC)

A CCC is mainly composed of a superconducting pickup coil, a highly effective superconducting shield, and a high performance SQUID measurement system (Fig. 1):

In principle, the CCC, first developed by Harvey in 1972, is a non-destructive method to compare two currents I_1 and I_2 (see Fig. 1) with the high precision of a SQUID. For that reason, the two currents are fed into a superconducting tube with a special pick-up coil as antenna. Using a meander-shaped flux transducer only the azimuthal magnetic field comonents which are proportional to the currents in the wires will be sensed by the SQUID. All other field components are strongly suppressed. A more detailed description can be found in [5].

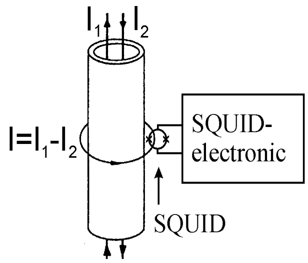

Fig.1: Principle of the Cryogenic Current Comparator

4. THE CHECHIA CCC DESIGN

The dark current CCC design is realized as co-operation of DESY, FSU and GSI. The instrument will be placed in the CHECHIA cavity test stand and operates at 4.2 K.

4.1 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 high permeability and low noise even at liquid helium temperatures. The material inhomogeneities of the core are averaged by complete encapsulation of a toroidal niobium coil.

4.2 Shielding Aspects

The resolution of the CCC is reduced if the toriodal pickup coil operates in presence of external magnetic fields. As external fields are in practice unavoidable, an effective shielding has to be applied. A circular meander-shaped shielding structure ("ring cavities", Fig. 2) is able to pass the azimuthal magnetic fields of the dark current, while strong attenuating non-azimuthal field components.
Using a superconductive shielding material like niobium leads to an ideal diamagnetic conductor, which implies the vanishing of all normal components of the magnetic fields at the superconductive surface. The attenuation characteristics of CCC shieldings were analyzed analytic in great detail [6-8]. Applied to the shielding of the proposed TESLA CCC with a inner radius of 69.0 mm, an outer radius of 112 mm, 14 "ring cavities" and a meander slot width of 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" (shown in [9]).

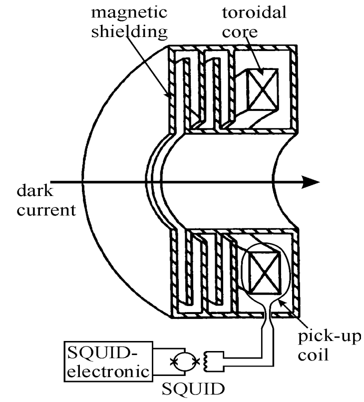

Figure 2: Schematic view of magnetic shielding, pickup coil and SQUID system

A numerical analysis was set up for verification. To compare with the analytic computations, first the numerical approach on the coaxial cylinders was tested. A pill box cavity was used to apply external fields of first order (magnetic dipole). In this way it was possible to use 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. The attenuation through the shielding structure at frequencies > 900 MHz is very high. It is in the negligible range of 200 dB. This gives confidence, that the strong 1.3 GHz component will be suppressed sufficiently.

4.3 SQUID Measurement System

The key component of the CCC is a high performance SQUID system developed and manufactured at the FSU Jena. A detailed description of the functional principle of the SQUID measurement system is given in [5].
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 provided from the SQUID electronics (Fig. 3). 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 307.2 kHz results in a bandwidth of about 70 kHz. Thus, it will be possible to characterize the pulse shape of the dark current beam (950 µs pulse length, 5 Hz repetition rate) which is overlayed by the RF structure applied to the cavities. Currently the SQUID measurement system is ready for use. The first measurements with all special cabling and feedthroughs were successfully done and a current system sensitivity of 167 nA/Φ_0

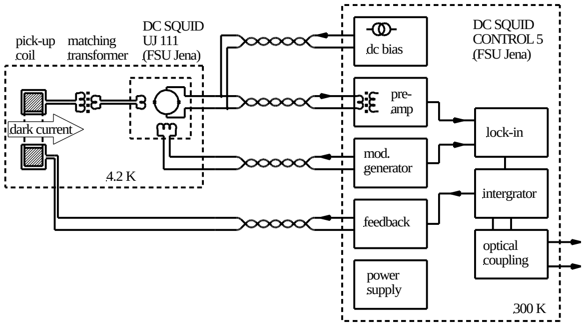

Figure 3: Simplified electrical scheme of the CCC

was achieved using a special pick-up coil to emulate the real pick-up coil under fabrication. The flux noise of the whole system was measured to be as low as 8 x 10^{-5} $\Phi_0/\sqrt{Hz}$ in the white noise region (see Fig. 5). These values correspond to a noise limited current resolution of the CCC as low as 13 pA/√Hz. According to our experience, in the final system the resolution will be decreased by at least one order of magnitude because of the additional noise contribution of the VITROVAC core of the pick-up coil.

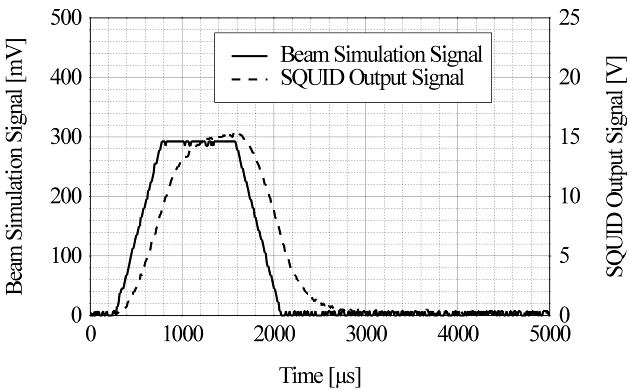

Figure 4: SQUID response and test signal

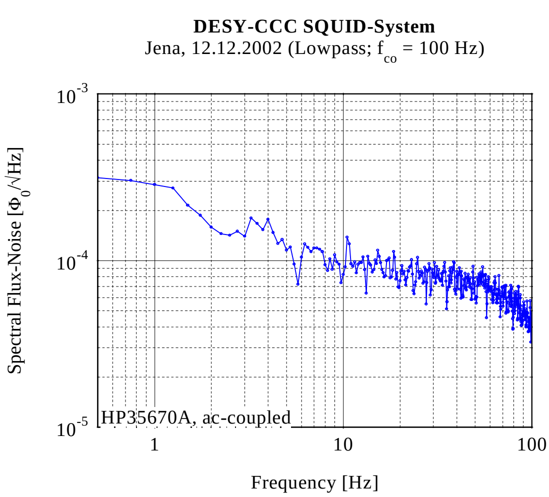

Figure 5: Spectral noise density

4.4 Faraday Cup

This design for the CHECHIA test stand includes a faraday cup in order to compare the CCC dark current measurements. Otherwise, the energy of the dark current electrons is so small that they will be stopped completely in a small faraday cup (Fig. 6). The current to ground will be measured by an electronics. A HV-screen will collect the secondaries from the stopper electrode.

In the TESLA cavity-module test stand the energy of the dark current electrons will reach much higher energies (Table 1). In this case the measurement with a faraday-cup is not possible. The size of the Faraday-cup will became very large and the HV-screen will not collect all of the electrons.

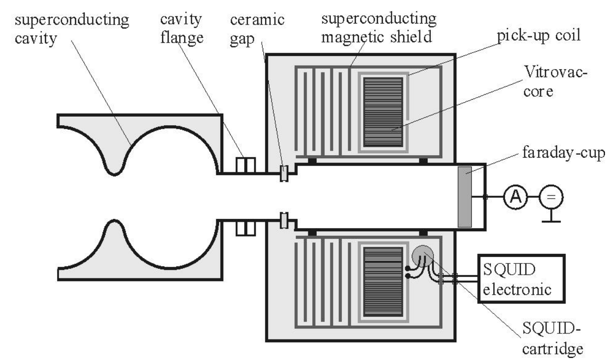

Figure 6: Schematic Design of the CHECHIA CCC

5. OUTLOOK

The mechanical construction of the CHECHIA CCC is completed and the fabrication started with the magnetic shielding and the pick-up coil, which are the most sophisticated mechanical parts.

The results of the next test-setup, consisting of the SQUID electronics and the completed superconducting shielding including the pick-up coil, will be shown at the EUCAS conference in autumn of this year.

6. REFERENCES

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