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 in 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 km long main linacs are equipped with a total of approximately 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 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 superconductiong field sensor (SQUID). The setup contains a faraday cup and will be housed in the cryostat of the CHECCIA 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 [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 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 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 (14x9-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 temperatures for the apparatus are of no problem, as the CHECCIA 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. At GSI Darmstadt a CCC detector system has demonstrated its excellent capabilities to measure nA beam currents in the extraction beam line heavy ion synchrotron [4].

3 CRYOGENIC CURRENT COMPARATOR PRINCIPLE

A CCC is composed of three main components (Fig. 1):
- A superconducting pickup coil,
- A high effective superconducting shield,
- A SQUID system.

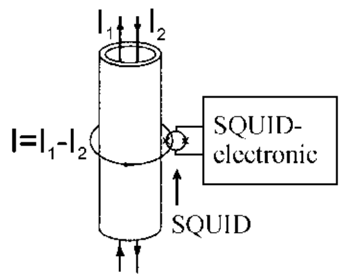

Figure 1: Principle of a Current Comparator

Principle of operation:
Two reverse currents are feed through a superconducting tube. They introduce a differential current on the surface of the tube (Meissner-Ochsenfeld-Effekt). The magnetic field of the differential current is measured with a SQUID, which provides the resolution of a magnetic flux quantum (2.07 x 10^{-15} Vs). A more detailed description can be found in [4].

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 slit around the circumference. It contains a Vitrovac 6025-F core (Vacuumschmelze GmbH, Hanau, Germany), which provides high permeability and low noise, even at liquid helium temperatures. The material inhomogeneity 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 toriod pickup operates in presence of external magnetic fields. As external fields are in practice unavoidable, an effective shielding has to be applied. A circular meander ("ring cavities") shielding structure (Fig. 2) is able to pass the azimuthal magnetic fields of the dark current, while strong attenuating non-azimuthal field components.

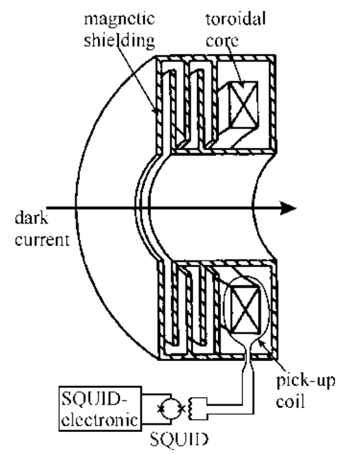

Figure 2: Schematic view of magnetic shielding, pickup coil and SQUID

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 analyzed analytic in great detail [5, 6, 7]. Applied to the shielding of the proposed TESLA CCC, with the dimensions:

Inner radius:	69.0 mm
Outer radius:	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 promised. 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 [8]).

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 pill box 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 [5] 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 confidence, that the strong 1.3 GHz frequency component will be suppressed sufficiently.

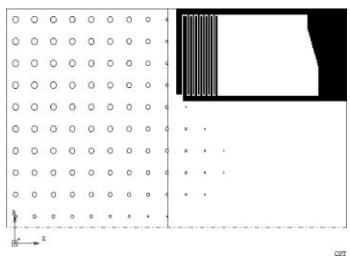

Figure 3: Numerical analysis of the shieding with the MAFIA eigenmode solver E

4.3 SQUID Measurement System

The key component of the CCC is a DC SQUID system developed and manufactured at the Friedrich Schiller University Jena. It consists out of two Josephson junctions in a superconducting ring arrangement and is able to sense a single magnetic flux quantum. 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 500 kHz in the complete measurement system, results in a bandwidth above 50 kHz. 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.

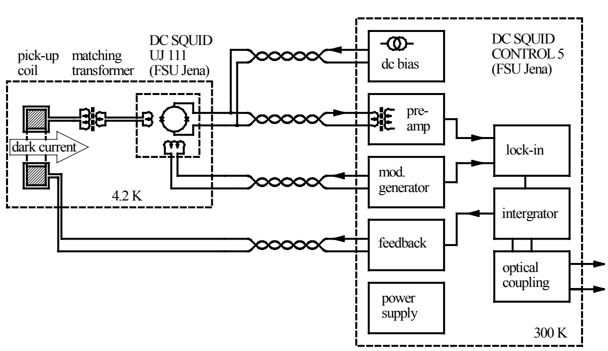

Figure 4: Cryogenic Current Comparator (simplified scheme)

4.4 Faraday Cup

Because at CHECHIA the energy of the dark current electrons is relatively small, the design includes a faraday cup in order to compare the CCC dark current measurements, we added a 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.

5. 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. Al mechanics hardware will be completed end 2002. The SQUID electronics including special cabling and feedthroughs are ready for installation. The final installation is planed spring 2003. A simplified scheme of the construction is shown in Figure 5.

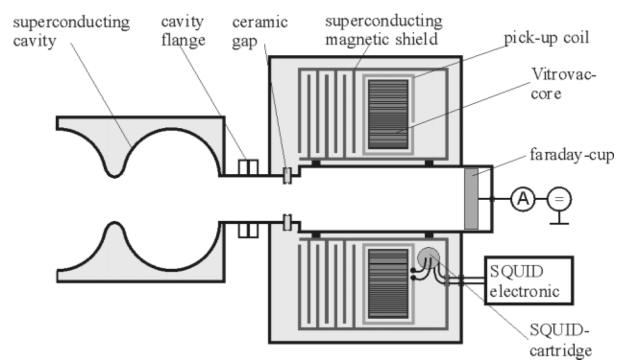

Figure 5: Schematic Design of the CHECHIA CCC

6. REFERENCES

[1] R. Brinkmann, et. al.; TESLA Technical Design Report

[2] R. Brinkmann; Dark Current Issues; TESLA Collab. Meeting - CEA Saclay 4/2002

[3] G. R. Werner, et. al.; Proc. of the Part. Acc. Conf. PAC 01, pp.1071-73

[4] A. Peters, W. Vodel, H. Koch, R. Neubert, C.H. Schroeder; Proc. of 8th BIW, Stanford, 1998, AIP Conf. Proc. 451

[5] K. Grohmann, et. al.; CRYOGENICS, July 1976, pp.423-429

[6] K. Grohmann, et. al.; CRYOGENICS, October 1976, pp.601-605

[7] K. Grohmann and D. Hechtfischer; CRYOGENICS, October 1977, pp.579-581

[8] P. Gutmann and H. Bachmair; in V. Kose, Superconducting Quantum Electronics, 1989, pp.255-259