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Dark current measurements on a superconducting cavity using a cryogenic current comparator

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This paper presents nondestructive dark current measurements of tera electron volt energy superconducting linear accelerator cavities. The measurements were carried out in an extremely noisy accelerator environment using a low temperature dc superconducting quantum interference device based cryogenic current comparator. The overall current sensitivity under these rough conditions was measured to be 0.2 nA/Hz$^{1/2}$, which enables the detection of dark currents of 5 nA. © *2011 American Institute of Physics*. [doi:10.1063/1.3527063]

I. INTRODUCTION

Although tera electron volt energy superconducting linear accelerator (TESLA) cavities were originally developed for operating in pulsed-mode like in the TESLA linear collider[1] or the European X-FEL (Ref. 2) at DESY Hamburg, many planned continuous wave (CW) driven linear accelerators (LINACs) for free electron laser (FEL) and energy recovery linacs (ERLs) will be based on similar cavities.

Dark currents are one of the limiting factors for cavities with high accelerating gradients. They might cause activation or damage of accelerator components[3] and induce quenches in superconducting cavities. Dark currents can excite unwanted higher order modes in the cavity and create a beam halo. They also put an extra load on the cryogenic system. For example, a dark current of 1 μA dumped into a 20 MV/m cavity will create an extra cryoload of 20 W. Thus, to analyze the quality of mass-produced cavities the measurement of the absolute value of the dark current as a function of the gradient of the acceleration field is necessary.[4] Configurations for complete module tests with many cavities will not allow the use of simple Faraday Cups because the energy of the dark current electrons might reach very high energies (some 100 MeV) so that they are not stopped by a Faraday Cup. In this situation, a cryogenic current comparator (CCC) provides a number of advantages over the measurement of dark currents utilizing a Faraday Cup:

- nondestructive measurements,
- measurement of the absolute value of the dark current,
- independence of the electron trajectories and energies,
- accurate absolute calibration with an additional wire loop, and
- extremely high resolution.

The suitability of a CCC as a beam monitor has already been demonstrated, see Ref. 5. Although the presented system was designed for the module test facility of the European X-FEL at DESY Hamburg, the measurements were carried out in the horizontal bi-cavity test-facility (HoBiCaT) at Helmholtz–Zentrum–Berlin (HZB). The HoBiCaT test facility was constructed to enable rapid-turn-around tests of nine-cell cavities with all the required ancillary components.[6] The CCC is mounted on one end of the cavity with a bellow in between. A ceramic gap is recessed in the bellow so that the magnetic field of the dark current can freely propagate through this gap and out of the beam pipe to the entrance slit of the CCC (see Fig. 1).

The presented apparatus senses dark currents in the nanoampere (nA) range. The setup also contains a Faraday Cup as a second measurement device for comparison. In the case of single-cavity operation in HoBiCaT, the Faraday Cup should work reliably (maximum possible electron energy is about 15 MeV).

II. CRYOGENIC CURRENT COMPARATOR

Originally developed to compare two currents with one another,[7] CCCs are used in many different ways in metrology, see, for example, Refs. 8 and 9.

The presented CCC consists of (see Fig. 2):

- a meander-shaped superconducting niobium shielding (for an enlarged view, see Fig. 2),
- a superconducting niobium single-turn toroidal pick-up coil with a ferromagnetic core, and
- a high performance dc superconducting quantum interference device (SQUID) system.

A. Superconducting shielding

The resolution of the CCC is reduced if the toroidal pick-up coil operates in the presence of disturbing external magnetic fields. In practice, external fields are unavoidable, therefore, an extremely effective shielding has to be applied.

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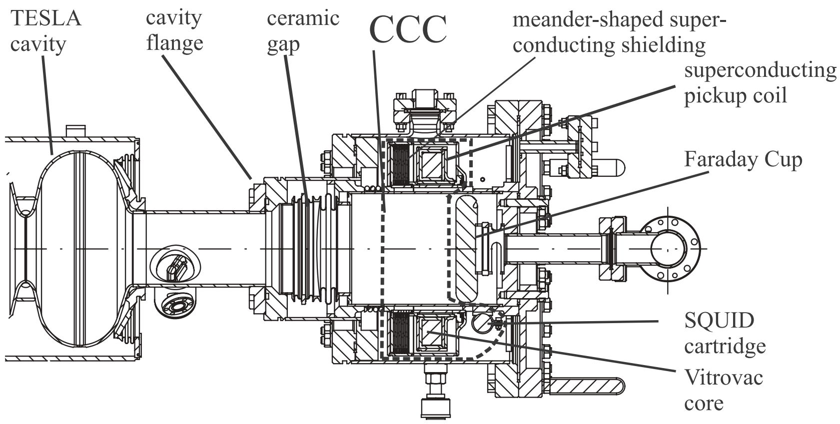

FIG. 1. Schematic view of the HoBiCaT test facility with the TESLA cavity, CCC, and Faraday Cup. The dashed line is added to indicate the CCC with its components.

A circular meander-shaped ("ring cavities") superconducting shielding structure (see Fig. 2) allows only the azimuthal magnetic field component of the dark current to pass, while the nonazimuthal field components are strongly attenuated. The attenuation characteristics of CCC shields have been studied analytically in detail in Refs. 10–12. These studies have been applied to the shielding of the presented CCC, and an attenuation factor of approximately 120 dB for the transverse, nonazimuthal magnetic field components is estimated. This result is based on the superposition of the analytic results for the different shielding substructures, in this case coaxial cylinders and ring cavities (as described in detail in Ref. 13).

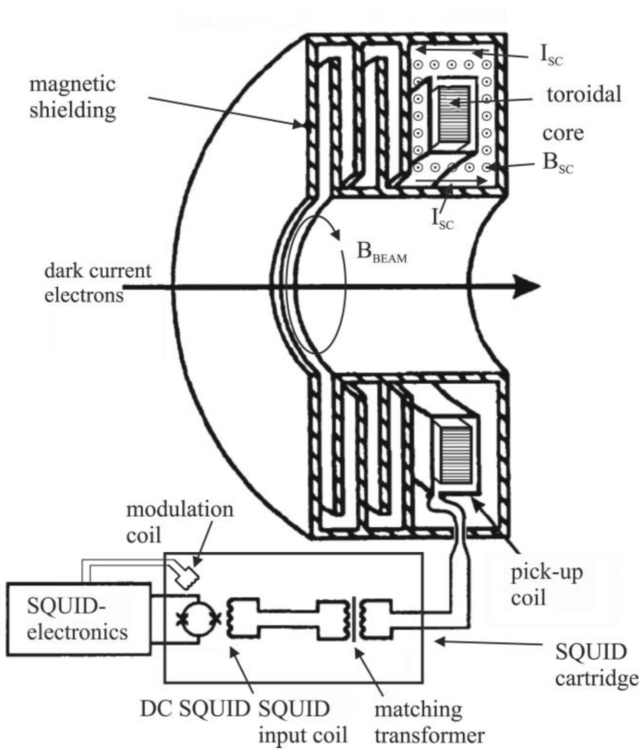

FIG. 2. Simplified schematic view of the meander-shaped magnetic shielding, the toroidal pick-up coil, the matching transformer, and the SQUID.

B. Pick-up coil

A single turn pick-up coil is formed as a superconducting niobium toroid with a slot around the circumference. It contains a Vitrovac 6025F core[14] providing a high permeability μ_r of about 18 000 at liquid helium temperatures (see Fig. 3). The relative permeability is calculated from the measured inductance of the installed pick-up coil. The measurement was done by an Agilent E4980A precision LCR meter; for details, see Ref. 15. The material inhomogeneity of the core is averaged by complete encapsulation of a toroidal niobium coil.

C. SQUID system

The key component of the CCC is the high performance dc SQUID system developed and manufactured at Jena University (see Fig. 4). The SQUID sensor UJ 111 (Ref. 16) is designed in a gradiometric configuration and based on Nb–NbO_x–Pb/In/Au Josephson tunnel junctions with dimensions of $3 \times 3\ \mu m^2$. The SQUID electronics consist of a low noise preamplifier and the SQUID control unit. The low source

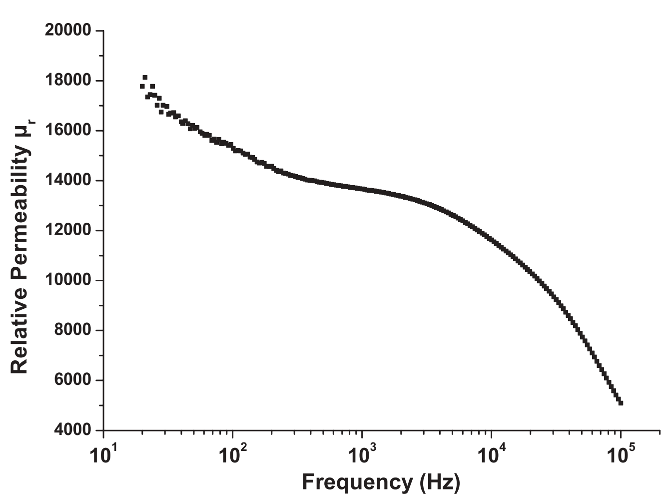

FIG. 3. Relative permeability of the ferromagnetic core material Vitrovac 6025F (Ref. 14) at 4.2 K.

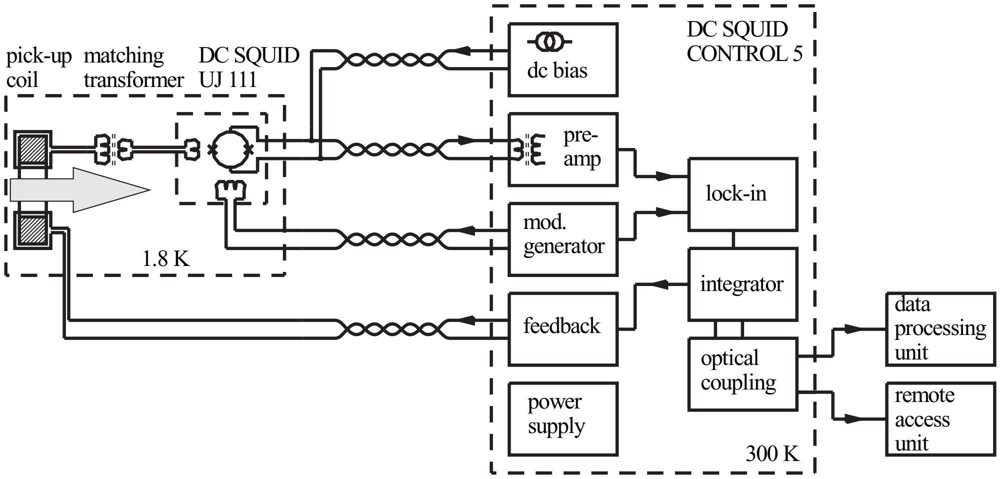

FIG. 4. Simplified scheme of the CCC with the high performance dc SQUID system of Jena University. On the left-hand side, the superconducting components at 1.8 K are shown. On the right-hand side, one can see the components of the SQUID electronics at 300 K.

impedance of the SQUID (about 1 Ω) is stepped up to the optimal impedance of the preamplifier by a resonant transformer. The dc bias and flux modulation (modulation frequency 307 kHz) are fed into the SQUID via a voltage-controlled current source situated in the preamplifier and the controller, respectively. An optimal choice of bias and flux modulation working point for the SQUID system was adjusted in the magnetic shielded room (MSR) manufactured by VAC Hanau.[14] In a dc coupled feedback loop, the field of the dark current to be measured is compensated at the pick-up coil by an external magnetic field generated by the attached electronics.

Due to the superconductivity of all leads in the input circuitry (shielding, pick-up coil, transformer, and SQUID input coil), the CCC is able to even detect dc. For an optimum coupling between the single-turn toroidal pick-up coil (26 μH @ 100 Hz, 4.2 K; relative permeability see Fig. 3) and the SQUID input coil (0.8 μH) a matching transformer is necessary. Using a modulation frequency of 307 kHz, the measurement system provides an overall bandwidth of 20 kHz (signal level 1 Φ_0) or 70 kHz (signal level 0.1 Φ_0).

D. Working principle of the CCC

The dark current electrons create a magnetic field B_{BEAM}, which induces screening currents I_{SC} in the meander-shaped superconducting shielding (see Fig. 2). These screening currents in turn generate a magnetic field B_{SC}, which is transformed into a current through the pick-up coil. This current is then measured by the SQUID, after passing and being transformed by the matching transformer.

III. MEASUREMENT SETUP

The output signals from the CCC and the Faraday Cup were captured by a computerized data acquisition system. The SQUID signal was connected to a National Instruments PCI-6221 (M series DAQ) card. The Faraday Cup was installed at the end of the cavity vacuum chamber (see Fig. 1). The Faraday Cup was biased with +210 V which was tested to be sufficient to collect all charges (the charge versus bias reached a plateau). For its biasing and readout a high resolution digital voltage meter (DVM) was used (Keithley 2400 Source Meter), which was connected via a general purpose interface bus (GPIB) to the computer to measure the collected dark current to ground after passing the CCC. The signals from the CCC and the Faraday Cup were captured simultaneously in two separate loops with the help of a customized program. The start and the end time as well as a separate measurement time created in each loop were logged to ensure a chronological correlation. The spectral current noise distributions were measured with a Hewlett Packard 33120A spectrum analyzer.

IV. RESULTS

The presented measurements of dark currents at the HoBiCaT test facility at HZB were performed on the DESY Z86 cavity. The operating temperature of the test facility including the CCC is 1.8 K by cooling with superfluid helium. The cavity could be operated either in CW or pulsed mode. The repetition rate in pulsed mode was chosen as 0.1 Hz, with 50% duty cycle.

As depicted in Fig. 5, the CCC signal is very noisy. Because of the high noise level of more than 1 Φ_0 the most sensitive measuring range of the SQUID electronics could not be used. In this environment, an overall current sensitivity of the CCC of 243 nA/Φ_0 could be achieved, which is equivalent to 243 nA/V with these settings. This is slightly less sensitive compared to Vodel *et al.*,[4] where the overall current sensitivity was specified to be 200 nA/Φ_0. This is due to a necessary reconstruction which caused a change of the inductance of the pick-up coil and, therefore, a change of the transfer ratio of the matching transformer.

As one can see in the spectral current noise distributions (see Fig. 6), there is a considerable noise contribution between 5 and 500 Hz while running the CCC in this disturbed accelerator environment. It is noticeable that there is no visible additional noise when the acceleration field is switched

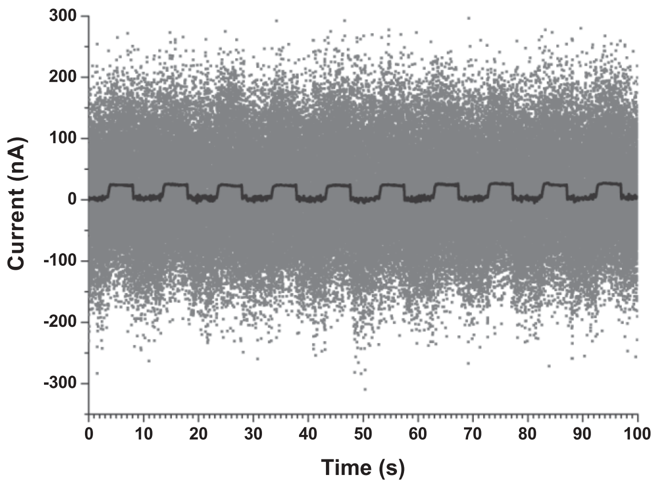

FIG. 5. Dark current from the raw CCC-SQUID-signal (gray), calculated with an overall current sensitivity of 243 nA/V. The black curve is the signal filtered by means of a 5 Hz low pass filter.

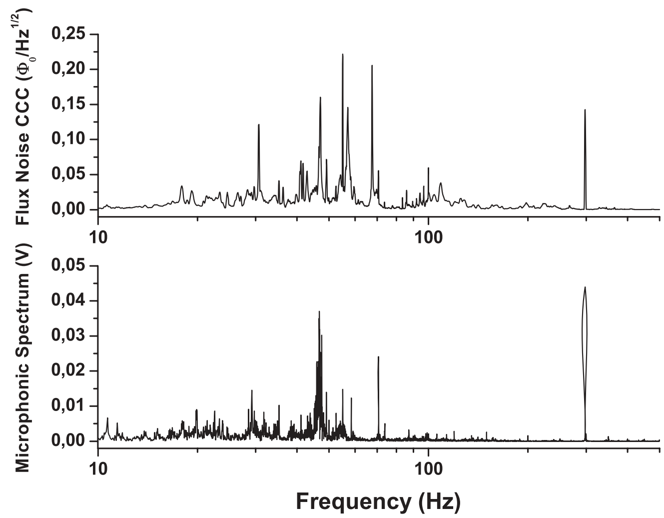

FIG. 7. Comparison between the spectrum of microphonic disturbances (lower curve) measured by HZB and flux noise spectrum of the CCC (upper curve).

on. The noise limited current resolution in the frequency range up to 5 Hz is 0.2 nA/Hz$^{1/2}$ with a total noise of 1.8 nA. Between 5 and 500 Hz, this increases to 50 nA/Hz$^{1/2}$ due to external disturbances. A major part of the additional noise seems to be caused by microphonic effects.

The peak at 300 Hz in Fig. 6, for example, is clearly assignable to the vacuum pump for the insulation vacuum of the HoBiCaT test facility. Neumann *et al.*[17] investigated the microphonic detuning of these cavities in the HoBiCaT test facility regarding the stability of the cavities resonant frequency. Several microphonic sources were identified with their corresponding frequencies. One can distinguish between deterministic narrow bandwidth sources, like vacuum, water, respectively, helium pumps, and random broadband machinery noise.

The frequency spectrum of microphonic disturbances was also measured for the DESY Z86 cavity. Compared with the measured flux noise of the CCC (see Fig. 7) microphonic effects could be confirmed as a source of many disturbances. The coupling of the vibrations of the HoBiCaT test facility to the CCC can be explained by a relative movement of the disks of the meander-shaped shielding against each other.

The pulsed dark current is clearly visible after filtering the signal with a low pass filter whose cutoff frequency of 5 Hz is below the additional noise contribution. In Fig. 8, a dark current of approximately 21 nA is measured with the Faraday Cup. After filtering and smoothing, the CCC shows similar results. As depicted in Fig. 9, it is possible to detect dark currents with an accuracy of several nA down to 5 nA within a 5 Hz bandwidth. Even down to 0.5 nA, the pulse sequence is detectable.

The drift in Figs. 8 and 9 can be explained by the superconducting properties of the CCC. Since the CCC is sensitive to dc and ac signals, it also detects slowly varying stray fields. These might be caused by temperature changes or charging of the test facility in pulsed operation mode.

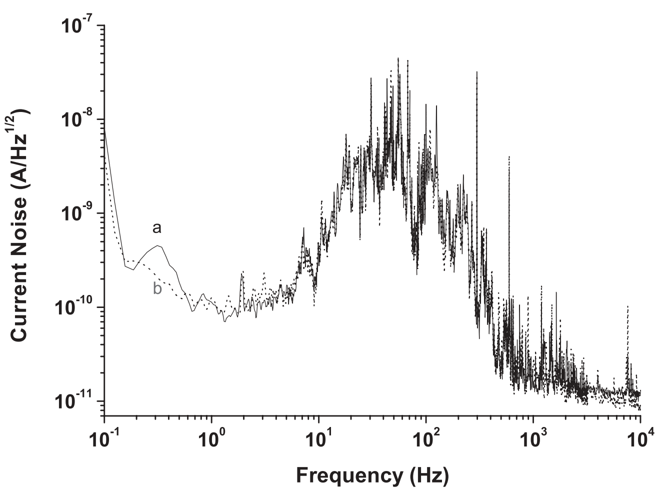

FIG. 6. Spectral current noise distributions of the CCC at HZB without acceleration field [curve (a); black], and with acceleration field [curve (b); light gray, dotted].

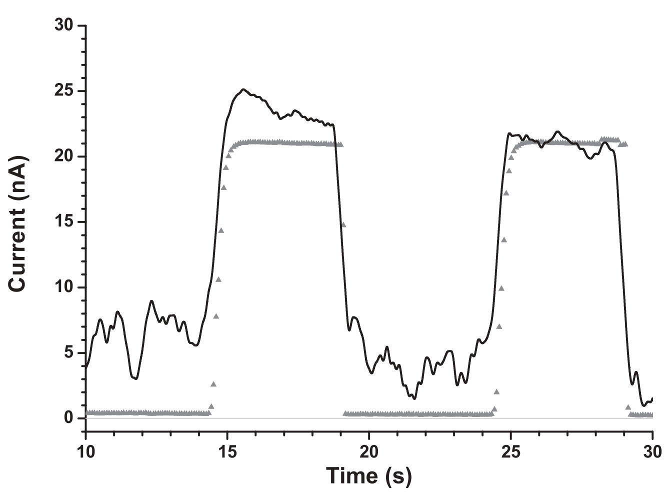

FIG. 8. Dark current of approximately 21 nA measured with the CCC (black curve, filtered and smoothed) and Faraday Cup (gray, triangles).

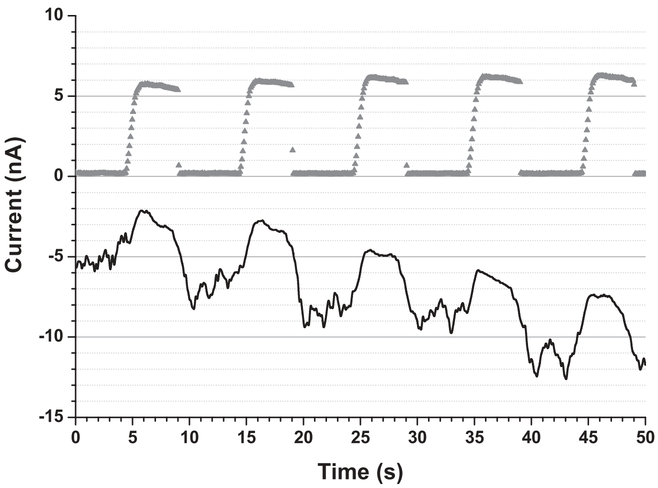

FIG. 9. Dark current of approximately 5 nA measured with the CCC (black curve, filtered and smoothed) and Faraday Cup (gray, triangles).

It is also striking that the plateau of the dark current when the acceleration field is switched on is not constant, but very slightly sloping. This behavior was observed in subsequent measurements at HZB on a much larger scale. Switching on the acceleration field much longer than 5 s led to a drop in dark current of more than 50%. This was due to a slow heating of higher order modes (HOM) couplers, which were installed in the cavity, so that the quality factor of the cavity deteriorated slowly. This led in turn to a smaller transmitted power or smaller cavity field and thus to a smaller dark current. The dark current reduced until a steady state of the HOM heating was reached. The time constant for this thermal process was several minutes.

V. CONCLUSIONS

The measurements at the HoBiCaT test facility demonstrated that our cryogenic current comparator is capable of measuring dark currents of superconducting cavities in an extremely noisy accelerator environment. The overall current sensitivity of the CCC was 243 nA/Φ_0. The expected[4] noise-limited current resolution of 0.5 nA/Hz$^{1/2}$ even was exceeded and was measured to be 0.2 nA/Hz$^{1/2}$ for frequencies below 5 Hz. In the frequency range between 5 and 500 Hz, the noise increased to 50 nA/Hz$^{1/2}$ due to external disturbances. These could be attributed in part to microphonic effects. An attenuation of this kind of disturbance might be achieved by fixing the disks of the meander-shaped shielding against each other. Nevertheless the nondestructive detection of dark currents down to 5 nA with an accuracy of a few nA in an accelerator environment was successful. Further improvements are possible by finding ferromagnetic core materials for the pick-up coil with a higher permeability and extended frequency range. This is part of ongoing investigations; some initial results are presented in Ref. 15.

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