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Surface superconductivity in niobium for superconducting RF cavities

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Abstract

A systematic study is presented on the superconductivity (SC) parameters of the ultrapure niobium used for the fabrication of the nine-cell 1.3 GHz cavities for the linear collider project TESLA. Cylindrical Nb samples have been subjected to the same surface treatments that are applied to the TESLA cavities: buffered chemical polishing (BCP), electrolytic polishing (EP), low-temperature bakeout (LTB). The magnetization curves and the complex magnetic susceptibility have been measured over a wide range of temperatures and DC magnetic fields, and also for different frequencies of the applied AC magnetic field. The bulk superconductivity parameters such as the critical temperature $T_c = 9.26$ K and the upper critical field $B_{c2}(0) = 410$ mT are found to be in good agreement with previous data. Evidence for surface superconductivity at fields above B_{c2} is found in all samples. The critical surface field exceeds the Ginzburg–Landau field $B_{c3} = 1.695 B_{c2}$ by about 10% in BCP-treated samples and increases even further if EP or LTB are applied. From the field dependence of the susceptibility and a power-law analysis of the complex AC conductivity and resistivity the existence of two different phases of surface superconductivity can be established which resemble the Meissner and Abrikosov phases in the bulk: (1) "coherent surface superconductivity", allowing SC shielding currents flowing around the entire cylindrical sample, for external fields B in the range $B_{c2} < B < B_{c3}^{coh}$, and (2) "incoherent surface superconductivity" with disconnected SC domains for $B_{c3}^{coh} < B < B_{c3}$. The "coherent" critical surface field separating the two phases is found to be $B_{c3}^{coh} = 0.81\, B_{c3}$ for all samples. The exponents in the power law analysis are different for BCP and EP samples, pointing to different surface topologies.

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1. Introduction

The proposed linear electron–positron collider project TESLA is based on superconductor technology for particle acceleration. For a centre-of-mass energy of 500 GeV (TESLA 500) an accelerating field of 23.4 MV/m is required in the 1.3 GHz nine-cell cavities which are made from pure niobium and cooled by superfluid helium at 2 K. The cavities for the TESLA Test Facility (TTF) linac are fabricated from 2.8 mm thick niobium sheets by deep drawing and electron beam welding. A damage layer of about 150 μm thickness is removed from the inner surface to obtain optimum performance in the superconducting state. For the TTF cavities this has been done so far by chemical etching which consists of two alternating processes: dissolution of the natural Nb_2O_5 layer by HF and re-oxidation of the niobium by a strongly oxidizing acid such as nitric acid (HNO_3) [1,2]. To reduce the etching speed a buffer substance is added, for example phosphoric acid, and the mixture is cooled below 15 °C. The standard procedure with a removal rate of about 1 μm per minute is called buffered chemical polishing (BCP) using an acid mixture of HF (40%), HNO_3 (65%) and H_3PO_4 (85%) in a volume ratio of 1:1:2. In the most recent industrial production of 24 TTF cavities an average gradient 26.1 ± 2.3 MV/m at a quality factor $Q_0 = 1 \times 10^{10}$ was achieved. The technology developed for TTF is hence adequate for TESLA 500 but considerable improvements are needed for an upgrade of the collider to 800 GeV (TESLA 800). A detailed description of the present status of the nine-cell cavity layout, fabrication, preparation and tests can be found in [3].

After many years of intensive R&D there exists now compelling evidence that the BCP process limits the attainable field in multi-cell niobium cavities to about 30 MV/m. This is significantly below the physical limit of about 45 MV/m which is given by the condition that the radio frequency (RF) magnetic field has to stay below the critical field of the superconductor, which for the type II superconductor niobium appears to be close to the thermodynamic critical field ($B_c \approx 190$ mT at 2 K).

An alternative surface preparation method is electrolytic polishing (EP). The material is removed in an acid mixture (for example HF and H_2SO_4) under the flow of an electric current. Sharp edges or tips are smoothed out and a very glossy surface can be obtained. Using electrolytic polishing, scientists at the KEK laboratory in Tsukuba (Japan) achieved gradients of up to 40 MV/m in single-cell cavities [4,5]. Meanwhile gradients of 35–40 MV/m have been obtained repeatedly in many 1.3 GHz single-cell test cavities [6–8]. Recently the EP technology has been successfully transferred to the nine-cell TESLA cavities yielding a record value of 39 MV/m in a multicell cavity [9].

The superiority of EP as compared to BCP can be partially understood in terms of the much reduced surface roughness. The sharp ridges at the grain boundaries of an etched niobium surface may cause local enhancements of the RF magnetic field and thereby lead to a premature breakdown of superconductivity at these localized spots. A model based on this idea, developed by Knobloch et al. [10], is able to explain the reduction of the quality factor at high field. However, a puzzling observation which does not fit into this geometrical picture was made during the CERN-DESY-Saclay R&D programme on the electropolishing of single-cell cavities [8]: after the EP and rinsing with ultrapure water the cavities failed to reach full performance but exhibited a strong decrease of quality factor when high fields were approached. Applying a 24–48 h "bakeout" at 120–140 °C to the evacuated cavity resulted in a dramatic improvement: very high gradients were accessible and the "Q drop" vanished. It should be noted that the EP treatment at KEK [4,5] already included a bakeout at 85 °C. The BCS surface resistance at 1.3–1.5 GHz is found to be reduced by a factor of 2 after baking [8,11]. However, by removing a layer of ~200–300 nm in steps of ~50 nm from the EP surface by "oxipolishing" the reduction in R_{BCS} is lost and the "Q drop" reappears [11]. The reduction of R_{BCS} during baking has been attributed to oxygen atoms diffusing either from the dielectric Nb_2O_5 layer or from intergrain niobium oxides/suboxides down to a depth of 200–300 nm [11]. For further