PREPARATION OF NIOBIUM COATED COPPER SUPERCONDUCTING RF CAVITIES FOR THE LARGE ELECTRON POSITRON COLLIDER

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Summary

Since 1980 development work has been carried out at CERN aiming at producing niobium coated superconducting RF cavities in the framework of the foreseen LEP energy upgrading above the initial 55 GeV. During 1987 a 4-cell LEP cavity without coupling ports has been successfully coated for the first time. Meanwhile, cathodes for coating the coupling ports were built and tested. The effort has been subsequently directed to preparing at least one (possibly 2) coated cavity(ies) to be installed in LEP during 1989. In parallel, the various production steps of these cavities were reconsidered in view of industrial production.

1. Introduction

The energy upgrading of LEP (the Large Electron Positron Collider presently under construction at CERN) from the initial 55 GeV to about 90 GeV will require the installation on the machine of about 200 4-cell superconducting cavities (SC) of 352 MHz frequency [1]. Each of these cavities should provide an accelerating field of 5 to 7 MV/m and a Q_0 value not lower than 3×10^9 at 5 MV/m and 4.2 K.

Traditionally, SC's are made of high purity Nb sheets by lathe spinning and welding. A development programme for cavities prepared in this way was started at CERN in 1979, their feasibility has been shown and prototypes have been ordered from industry [2]. This type of cavity suffers from the relatively poor thermal conductivity of Nb at liquid helium temperatures. This may result in thermomagnetic breakdown of the cavity, because it permits the inner cavity surface to exceed the critical temperature whenever a local surface defect results in a large RF power absorption.

To minimise this risk, the purity of Nb has been increased and its thermal conductivity enhanced from 10 to about 80 $Wm^{-1}\ K^{-1}$ with beneficial effects on cavity stability.

Another possible solution to this problem consists in reducing the thickness of the superconducting Nb by coating with a Nb thin film a cavity made of high purity copper (OFHC, with thermal conductivity at 4.2 K of about 400 $Wm^{-1}\ K^{-1}$). Due to the Meissner effect which limits the RF field penetration in a superconductor to a very thin superficial layer, a Nb film 1 µm thick is sufficient to shield completely the more resistive underlying copper substrate. In addition to the higher thermal stability, the Nb/Cu solution brings about other advantages, namely a surface free from macroscopic resistive inclusions and a saving on the cost of Nb. Furthermore, as more recently discovered [3] Nb coated cavities are insensitive to the presence of external static magnetic fields. This feature renders superfluous the often complicated magnetic shielding. For these reasons, a development programme was undertaken at CERN in 1980, aiming at producing SC's by coating copper cavities with Nb films.

2. Experimental procedure and results

2.1 Preparation of cavities

The half-cells of copper cavities (diameters of 520 and 752 mm for the 500 MHz and the 352 MHz cavities respectively) are made by lathe spinning in the same way as those of bulk niobium. The half cells are subsequently welded by an electron beam (E.B.) gun. Due to the difficult access to the inside of the cavity, the equatorial weld was initially carried out from the outside, and completed by an internal 'cosmetic' weld. This latter weld, performed from the iris aperture of the cavity, removes only the surface irregularities without penetrating very deeply. It was found that, under the action of repeated chemical treatments, the cosmetic weld may be partially eroded, resulting in retention of chemicals in the weld (see section 3). For this reason all cavities are now welded from the inside by means of a specially designed E.B. gun.

Prior to Nb coating, the cavities are chemically cleaned by means of a chemical solution developed for this purpose [4] and carefully rinsed with demineralised water at 6 bars. Usually, after coating and measuring, the cavity is reused for another coating. To do so, the Nb film is chemically removed and then the cavity is chemically cleaned in the standard manner.

2.2 Coating procedure and results on single-cell 500 MHz cavities

For the coating of Cu cavities, sputtering was chosen in preference to other coating methods, as for instance chemical vapour deposition, evaporation or ion implantation, for its intrinsic simplicity and also because it does not require heating the cavity at high temperatures, which could result in copper annealing and cavity deformation.

The sputter-coating was initially carried out by means of a bias diode configuration [5][6]. This method consists in producing an argon gas plasma at a pressure of about 5×10^{-2} torr by biassing 3 Nb cathodes at about 1400 V (negative with respect to the cavity at ground potential). The cathodes, ideally parallel to the surface of the cavity, are rotating inside the latter during the coating process. Positive argon ions, hitting the cathodes under the effect of the applied electric field, sputter off from it Nb atoms, which condense on the cavity walls. About 15 single-cell 500 MHz cavities were produced by diode sputtering, showing that RF accelerating fields and Q values comparable to those of bulk Nb cavities could be obtained, together with the expected higher thermal stability [6].

Since 1985 a mechanically simpler cylindrical magnetron sputtering configuration has been designed and employed as an alternative to the diode configuration (see Fig. 1).

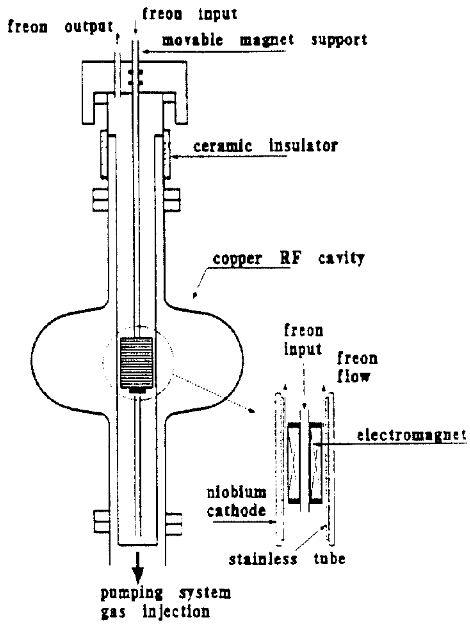

Fig. 1 : Schematic layout of a single-cell 500 MHz cavity with magnetron cathode

The cathode here is a stainless steel tube (100 mm diameter) located in the centre of the cavity parallel to its symmetry axis and surrounded by a Nb liner. The stainless steel tube contains a coaxial solenoid which provides a magnetic field of about 1.4×10^{-2} T at 60 mm from the central axis. Both the stainless steel cylinder and the solenoid are cooled during operation by circulating freon. The superposition to the electric field, perpendicular to the cathode, of a magnetic field parallel to the cathode results in trapping of the plasma electrons in close trajectories, therefore enhancing their ionisation efficiency, and providing higher deposition rates at lower operating pressures [7]. Coatings 1 µm thick may be obtained with magnetron sputtering in about 1 hour, to be compared with about 20 h required to obtain the same thickness by diode sputtering. Since the discharge is now confined by the presence of the magnetic field, the geometry of the source of Nb atoms may be varied by varying the length of the solenoid. This feature was taken advantage of to produce films with good thickness uniformity (about 20%) on the cavity cell keeping the solenoid at a fixed central position. Thickness uniformity in the cut-off tubes was achieved by moving the solenoid either at constant speed or in various steps at short intervals.

The optimisation of the deposition parameters was carried out at first on samples coated at different locations inside a stainless steel cavity especially conceived for this purpose and then on 500 MHz single-cell cavities. About 30 such cavities have been coated up to now by magnetron sputtering. Most of them with a cathode voltage of either 700 or 400 V negative with respect to the cavity (ground) potential. In either case, the magnetic field was adjusted to provide the same discharge power of 3 kW at constant argon pressure [8].

The majority of the results so far obtained are grouped in Fig. 2. This figure shows that the results obtained at 400 V are distinctly better than those obtained at 700 V. For the 400 V case, the cavities so far coated present a Q_0 value at 5 MV/m of at least 2×10^9, which is higher than the value specified for LEP cavities when scaling for the

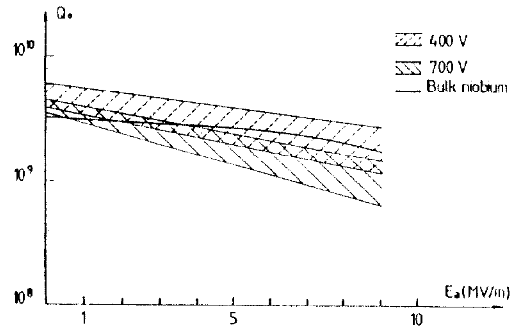

Fig. 2 : Performance of 500 MHz cavities coated at 400 V and 700 V compared to that of the best cavity made of bulk Nb

different frequency (Q_0 at 352 MHz ≈ 2 Q_0 at 500 MHz). For all cavities coated both at 400 and at 700 V the Q_0 value at low field but also the slope of the measured $Q_0(E)$ curves are larger than for cavities of bulk Nb. It has been hypothesized that both these features may be a consequence of the higher impurity content of the film (compared to bulk Nb) which also results in lower RRR values [3].

Looking for larger RRR values it was discovered that they could be obtained by increasing the deposition rate and/or the sample temperature during coating. For instance, at the equator of the cavity, RRR values of about 14 for samples coated at 400 V and kept at room temperature during coating are obtained, while RRR values of about 25 and up to 34 were measured on samples coated at 200°C and 400°C respectively. For mechanical stability reasons, copper cavities of the present geometry cannot be heated to above about 200°C while they are under vacuum. The results obtained for 500 MHz single-cell cavities coated at 85°C and 180°C are shown in Fig. 3, where they are compared with the performance of an average cavity coated at room temperature. The two cavities coated at higher temperature are both better than the others, and furthermore that coated at higher temperature (curve C in Fig. 3) presents a $Q_0(E)$ slope much smaller than usual for coated cavities, approaching the slope of bulk Nb cavities. This fact, if confirmed by further measurements, may result in producing Nb/Cu cavities with higher Q_0 values at 5 to 7 MV/m. It is also remarkable that the cavity C has reached 15 MV/m and that $Q_0 = 2 \times 10^9$ at 10 MV/m.

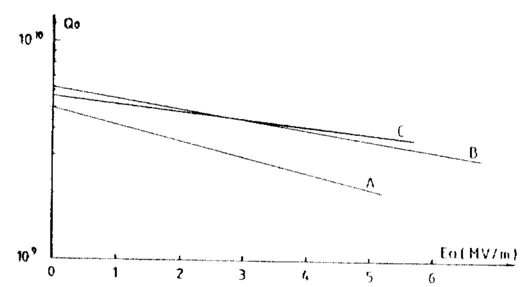

Fig. 3 : Influence of coating temperature on $Q_0(E)$ for 500 MHz cavities

curve A : room temperature
curve B : 80°C
curve C : 180°C

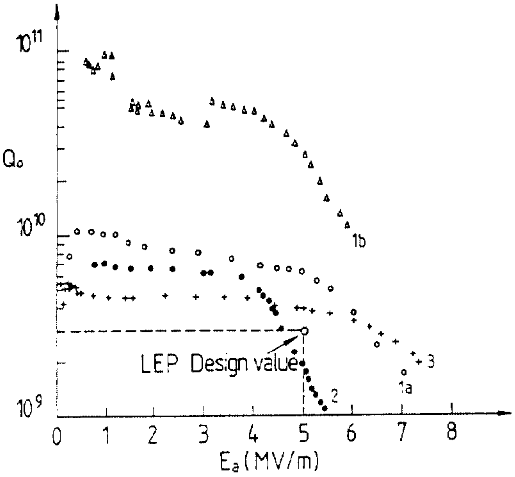

Fig. 4 : $Q_0(E)$ for 352 MHz four-cell coated cavities and for the best bulk Nb cavity.
curve 1 : Cavity coated at room temperature (without coupling tubes) measured at 4.2 K (1.a) and at 2.3 K (1.b).
curve 2 : Cavity coated at 200°C (with coupling tubes) measured at 4.2 K.
curve 3 : Bulk Nb cavity also measured at 4.2 K.

3. Four-cell cavities

The coating procedure as established for single-cell 500 MHz cavities was also applied to produce 4-cell cavities of 352 MHz frequency. In this latter case, the cathode diameter is 130 mm and the coating of the cells is carried out in sequence, placing the same solenoid in turn in the centre of each cell. Coating the inside of the coupling tubes, not present on the single-cell cavities, is carried out by means of a small diode system specially conceived for this purpose. Up to now, 8 coatings have been carried out by magnetron sputtering on 4 different cavities, of which only one was complete with coupling tubes. Of these coatings, six were unsuccessful, i.e. the corresponding cavity performance was below LEP specifications. The performance of the two 'good' cavities is depicted in Fig. 4 where, for comparison, the performance of the best 4-cell cavity made of bulk Nb is also shown. Of these two good cavities, cavity 1 has been coated at room temperature and cavity 2 (complete with coupling tubes) at about 200°C. These results seem to confirm that, as observed on single-cell cavities, room temperature coating results in a higher Q_0 at low field but also in a larger slope of $Q_0(E)$, that coated cavities provide higher Q_0 values than bulk Nb cavities and that high temperature coating results in a drastic slope decrease of the $Q_0(E)$ curve. It is worth noting that cavity 1 has a Q_0 value at 5 MV/m about a factor 2 larger than specified for LEP. Unfortunately, on cavity 2 the helium processing which is required to obtain on LEP cavities the specified Q_0 value had to be stopped for accidental reasons after only 22 hours (the standard duration of this operation is 50 to 60 h). For this reason, Q_0 at 5 MV/m is only 1.7×10^9, i.e. below LEP specifications. However, an extrapolated value of 6×10^9 may be expected on the ground of past experience whenever a helium processing of standard duration is applied.

The causes of the unsuccessful coatings are the following. Three coatings, carried out on the same copper cavity, presented large blisters in equatorial position, caused by the presence of chemical products at the cavity-film interface. These products were found to originate from the equatorial weld because of the partial destruction of the 'cosmetic' weld by the chemical treatment. The chemicals, which had deeply penetrated into the weld, could not be removed by rinsing. Chemicals, this time captured inside deep pits present on the copper surface, also spoiled the performance of another cavity. Two other cavities suffered from the presence of foreign particles which entered the cavity during assembling of the cathode.

4. Towards series production of Nb/Cu cavities for LEP

The results described here show clearly that Nb/Cu cavities for LEP are feasible and that, whenever coating is successful, their performance is superior to that of bulk Nb cavities. However, the reliability of the coating process, which is essential to envisage industrial series production, must still be proved. The first step in this direction is obviously to remove all the systematic problems which have been encountered so far. All cavities will be welded at the equator, as cavities 1 and 2 in Fig. 4 have been, with an internal E.B. gun, then removing the risk of weld opening and retention of chemicals. Internal welding will also reduce weld porosities and copper projections and result in a smoother weld surface [9]. The risk of surface pitting by the chemical treatment due to human mistakes has been taken care of by completely automatising the chemical treatment. As a second line of defense against the retention of chemicals on the copper surface prior to coating, it is planned to increase the rinsing water quantity and raise the water pressure from 6 to about 100 bars. Finally, the construction of a class 100 clean room large enough to permit cathode assembly has been planned to reduce the risk of presence of foreign particles in the cavity before coating. In addition, some improvements are also envisaged for the cathode. The ceramic insulation (Fig. 1) will be made independent of the cathode and mounted on two flanges such that it becomes easily replaceable in case of failure. Enough solenoids will be inserted in the cathode to avoid the need of moving them and the consequent risk of wrong positioning.

These improvements will be implemented before mid 1989. We hope that at the end of 1989 the required evidence will exist to make a sound choice between Nb/Cu and bulk Nb cavities for the LEP energy upgrading programme.

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