LARGE-SCALE INDUSTRIAL PRODUCTION OF SUPERCONDUCTING CAVITIES

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Abstract

Many laboratories around the world, notably CEBAF, CERN, DESY and KEK, after a period of research and development, are presently or have recently been involved in the industrial production of a large number of RF superconducting cavities. CERN, instead of using the standard bulk niobium technique, has developed a new Nb/Cu technology (niobium film deposited by magnetron sputtering on copper). The aim of this paper is to present the transfer of this technology to three European firms [Ansaldo, CERCA and Siemens (now ACCEL)]. Emphasis will be placed on the major challenges to industry of mastering the very complex procedure (which requires high quality control at every stage of the production) needed to achieve a very demanding final RF performance [Q(6 MV/m) = 3.4×10^9 at 4.5 K].

1 INTRODUCTION

In the last two decades many laboratories around the world decided to develop the technology of superconducting accelerating cavities. The aims were to increase the accelerator energy and to save electrical consumption. At first such cavities were made of niobium sheet metal but, unfortunately, the accelerating fields which could be obtained were limited by quenches. Since the level of power loss of a cavity is limited by the thermal conductivity of its wall, the efforts of the designers were concentrated on improving the Nb purity, in order to increase this thermal conductivity at liquid helium temperature.

An alternative solution consists of replacing Nb with copper as the material for cavity construction and depositing a thin Nb film (~1.2 µm) on the copper (Nb/Cu cavities). This approach offers inherent advantages: considerably higher stability against quenching, insensitivity to small magnetic fields and a higher quality factor than that of solid Nb at a given frequency and working temperature (4.2-4.5 K). It is evident that by replacing bulk Nb with an Nb layer an important saving is achieved, even allowing for the additional cost of the more elaborate fabrication procedure. An interesting feature is the possibility of replacing Nb with a wider choice of superconducting materials [1].

After a period of research and development, including the manufacture of a prototype series, CERN decided in 1990 to transfer this technology to industry. It awarded the contract for manufacturing the cavities and modules (four cavities assembled together) to three European companies, stipulating RF acceptance tests at 4.5 K. The decision to split the production of the Nb-coated cavities between three manufacturers was taken bearing in mind that the procurement of these superconducting cavities was the most critical aspect of the LEP upgrade program (entailing the mastery of many different complex technologies) and also in view of the very tight delivery schedule.

For the LEP upgrading project the total number of Nb/Cu cavities is 256 (64 modules) providing 2.6 GV as the accelerating voltage E_{acc}.

2 RESEARCH AND DEVELOPMENT AT CERN

2.1 Cavities

In 1980 a development program aiming at the production of coated SC RF cavities was started at CERN. The coating was achieved by sputtering using initially a bias diode configuration [2]. At the end of 1984 a series of 15 single-cell 500 MHz cavities was produced, demonstrating that the accelerating fields and Q values are higher than those of bulk Nb. A new electrode design was developed based on a cylindrical magnetron sputtering configuration. This offered several advantages: increased sputtering rate, better adhesion and uniform thickness of the film. Using this technique, a small series of LEP cavities (350 MHz) (12 cavities, three modules) was produced and installed in the LEP tunnel in order to obtain information on long-term performance and to check reproducibility of performance. One of the major problems met in the research and development program was the substrate preparation before Nb coating. It turned out that in order to avoid “peel-off” of the Nb film any contamination must be avoided; in other words a cavity which has a total surface of about 6 m^2 must be as clean as the silicon wafers of 20 cm^2 surface used in the manufacture of VLSI (Very Large Scale Integration) integrated circuits. A special chemical treatment was developed at CERN for the whole cavity, and the most critical phases of production, such as magnetron installation on the cavity, rinsing and drying, were carried out in a class 100 clean room.

2.2 Cryogenic Components

It became apparent quite early that the final cryostat design needed some novel construction concepts to

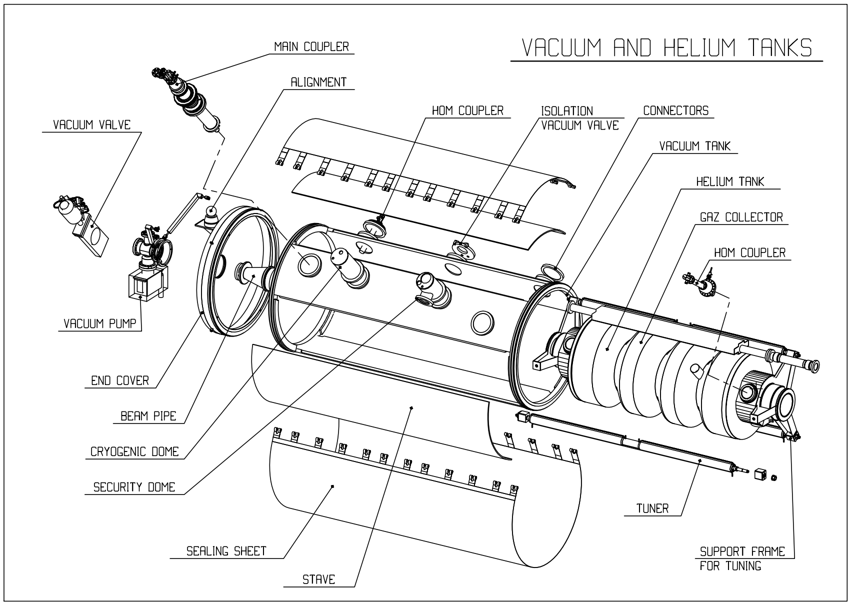

Fig. 1. Vacuum and helium tanks

minimize the costs, to meet the requirements of high accessibility to all critical parts such as couplers and to maximize the average accelerating field.

For these purpose a special vacuum vessel was designed and developed at CERN [3]. This consists of a cylindrical structure made of aluminum alloy; the main supporting frame of the vessel is made of two end rings and three longitudinal plates which are welded to the two rings. Two stainless-steel-sheet sealing envelopes are wrapped around the cylindrical structure. This kind of design allows easy access to all cavity components and it turned out that this was very important during the project because, due to technical difficulties and delay experienced with the couplers, RF and HOM (Higher Order Mode) couplers had to be installed at CERN on the modules already accepted.

Another cryogenic component developed at CERN is the helium tank which encloses the cavity. The design was aimed at minimizing the volume of liquid helium (safety in the LEP tunnel). The tank is made of 2 mm thick stainless-steel sheet welded throughout. Its main body consists of two half-shells which match the shape of the cavity. The seal between the cavity and the helium tank is achieved at the stainless steel ™Conflat flanges which equip all the ports (beam tubes and couplers). Thus the copper seals of all ™Conflat flanges merely separate the ultra-high machine vacuum (inner cavity volume) from the thermal insulation vacuum.

3 PRODUCTION SEQUENCE

3.1 Cavity Production

The major challenge for CERN was to help industry in mastering very quickly (six months) many different technologies, i.e. electron-beam (EB) welding, ultra-high vacuum, chemical cleaning, Nb sputtering, clean-room operation and provision of high-purity water facilities. In most cases even large industrial companies can master only some of these technologies.

The cavity half cells are produced by lathe spinning. The beam tubes are rolled, EB welded longitudinally and ball-extruded to create the power and HOM coupler ports. The beam tubes, as well as the half cells, are degreased, electropolished (120 µm n–butanol, phosphoric acid) and rinsed with demineralized water. The electropolishing is applied in two steps (~ 60 µm each); between these the surface is inspected visually and if necessary surface flaws are removed. ™Conflat type flanges are brazed to the coupler and beam tube ports. All parts are joined by EB welding using the internal gun technique. The entire cavity is degreased, filled with sulphamic acid, chemically polished (~ 20 µm, sulphamic acid, n-butanol, hydrogen peroxide and ammonium citrate), rinsed with sulphamic acid, high-purity water (18 MΩ/cm) and alcohol and dried under clean laminar air flow (Fig. 2).

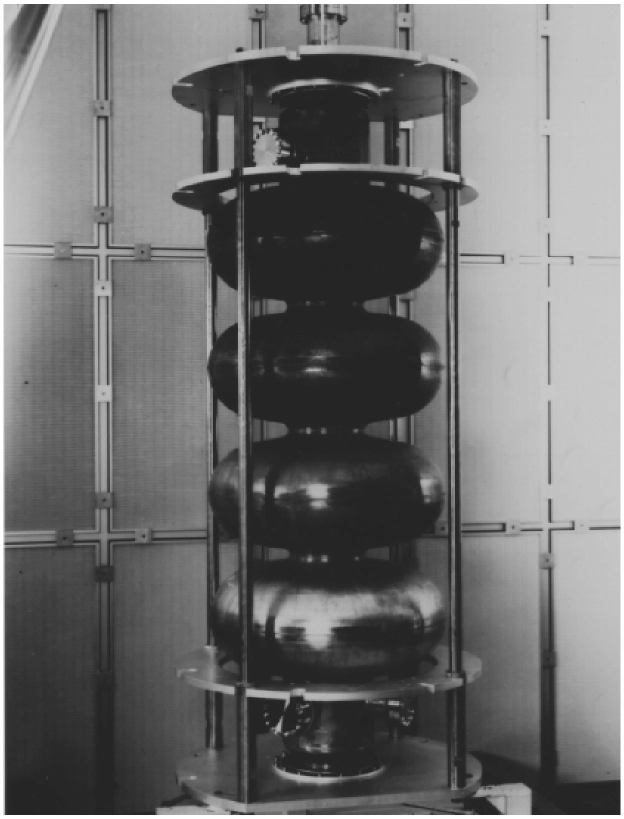

Fig. 2. Cavity in clean room

For Nb sputtering the magnetron cathode is mounted and dismounted on the cavity in a class 100 clean room. After coating the cavity is closed, rinsed with high purity water (18 MΩ/cm), dried by pumping and vented with filtered (0.2 μm pore size) dry nitrogen gas. The cavity is then ready to be shipped to CERN for the first RF test in a vertical cryostat. If the cavity does not attain the required performance, an attempt is made to localize the defects by temperature mapping and to recover the cavity by helium processing (24 hours), or if necessary by water rinsing (at low or high pressure). If this is unsuccessful the defective Nb layer is chemically removed and the cavity returned to the manufacturer for a second or even a third Nb coating. In view of the very demanding contractual RF specifications [Q at 6MV/m of at least 3.4×10^9 at 4.5 K] the intermediate RF test on the vertical cryostat was found to be absolutely fundamental for the production sequence.

Temperature mapping and visual inspection were also necessary tools for detecting and classifying different kinds of defects. By far the greatest number of “hot spots” detected on cavities during the RF tests were caused by non-uniform interface structure which reduced thermal contact between the Nb layer and the copper bulk [4]. This is clearly related to failures in the chemical polishing, water rinsing and drying of the copper surface before coating.

3.2 Module Production

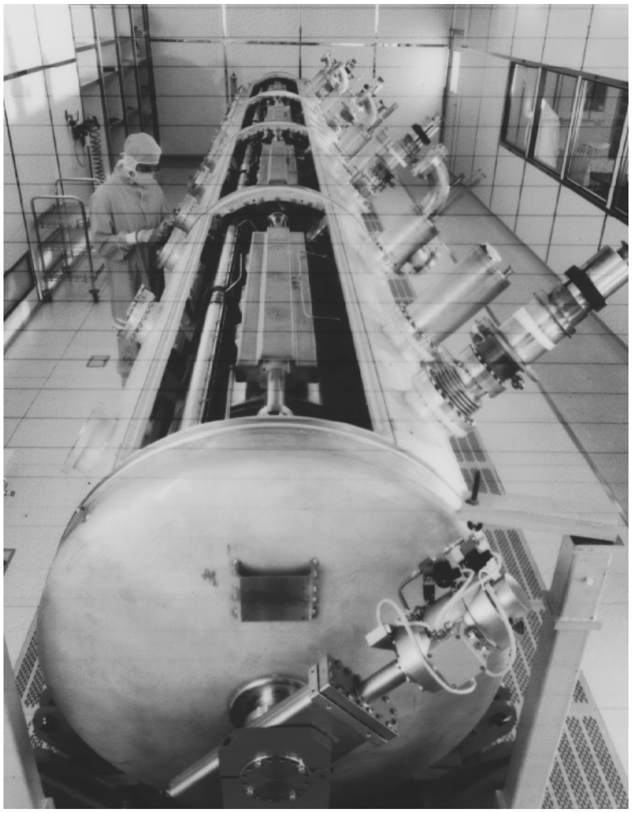

Fig. 3. Assembly in clean room

After the intermediate test at CERN described above, whereby the quality of the Nb coating was checked, the cavities were returned to industry for assembly into modules (four cavities, 12.5 m total length). The critical operation was the connecting of the large diameter (Ø = 24 cm) beam tube bellows which had to be done in a class 100 clean room (Fig. 3). Best results are obtained if this operation is done in as short a time as possible to minimize the risk of contamination. After mounting of the ancillary equipment (tuners, helium piping etc.) within the cryostat, the modules are sent to CERN, without the HOMs and RF couplers, for final acceptance.

4 ANALYSIS OF THE INDUSTRIAL PRODUCTION

4.1 Cavity Production

The most critical step in cavity production is the substrate preparation before Nb sputtering which, if not properly done, usually results in “peeling off” of the Nb film. Detached areas are typically of the order of some square millimeters which might seem small compared to the 6 m^2 of inner surface but is unfortunately sufficient for completely spoiling a cavity. Possible failures during surface preparation could be related to stains of chemical products on the surface, insufficient degreasing, liquid retention in pits, areas with varying copper structure introduced during the lathe-spinning or the electro-polishing, or mechanical damage to the surface.

Another possible mechanism of defect creation is foreign particles sticking on the cavity surface before and/or after coating. These can be either dust particles introduced during the manipulation or operation of the cavity or metal splinters from gaskets or tooling. In order to assure the success of this delicate phase of cavity production, a very careful quality protocol of procedures was agreed upon with the three firms. It must be stressed that the visual inspection of the cavity after chemical treatment (and after grinding off of any localized defects) is a critical step. In fact the most important component of the technology transfer was to formulate a precise quality control procedure.

Figure 4 shows the best performances among the 200 cavities already tested vertically so far. The Q-factors are consistently higher than the specifications (by 25% on average). Figure 5 shows the performance of the accepted cavities (Q at 6 MV/m) as a function of the year of production. There is a clear trend towards higher values showing that the firms gradually learned how to produce better and better cavities.

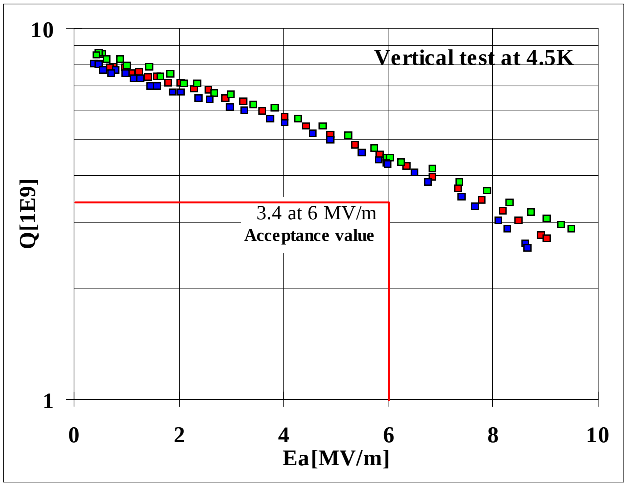

Fig. 4. Performance of the best LEP cavities

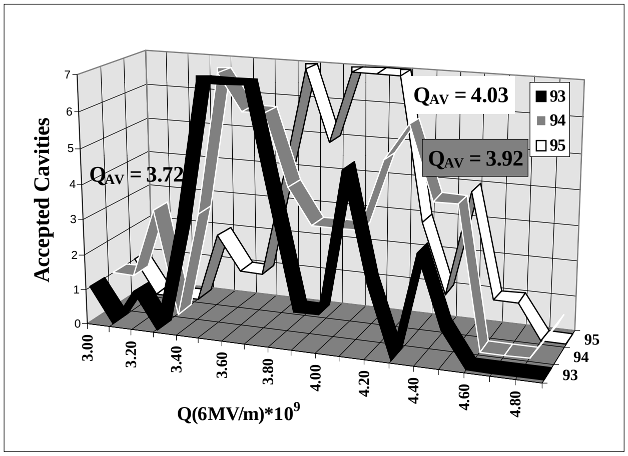

Fig. 5. LEP cavity performance *vs.* year of production

At present the success rate after a single coating is about 75%, but at certain periods of the series production, one company managed to produce 20 consecutive flawless cavities.

4.2 Module Assembly

Most of the problems encountered up until the final assembly were related to clean-room technology. Working in a clean room requires not only a sequence of precise procedures but also the development of a special behavioral "culture". Companies who succeeded in creating this "culture" with competent people and adequate equipment showed a zero rejection rate! Companies whose personnel were less well trained and where the equipment was inadequate experienced a rejection rate as high as 50%. At present, all three companies can reach the required performance levels, in some cases even without helium processing. No significant degradation of the Q *vs.* E_{acc} curve was observed [1].

When there was doubt concerning possible dust contamination during the assembly operations in the clean room, it was found important not to continue the operation, but rather to recheck the cavities, possibly recovering them by rinsing before completing the assembly of a full module. It should be kept in mind that the module assembly is the last critical step in a four- to five-month fabrication sequence, and that only absolutely minimal risks should be accepted.

5 CONCLUSION AND FUTURE

The new technology developed at CERN, Nb sputter-coating of copper cavities, has now become an industrial reality. Three European firms are able to produce SC cavities (from sheet metal to the final product) having very high level RF performance at liquid helium temperature. It has to be emphasized that thanks to the transfer of this technology from CERN to the three firms, they can now handle different techniques such as electron-beam welding, ultra-high vacuum, clean-room work, the implementation of large chemical and high-purity water plants, sputter-coating etc.

We have achieved strict adherence to our production plan by three separate companies. In Fig. 6 the total number of accepted cavities *vs.* time shows a constant and uninterrupted production rate. Using three suppliers ensured a steady production rate even if one or the other of the companies experienced a temporary loss of capacity.

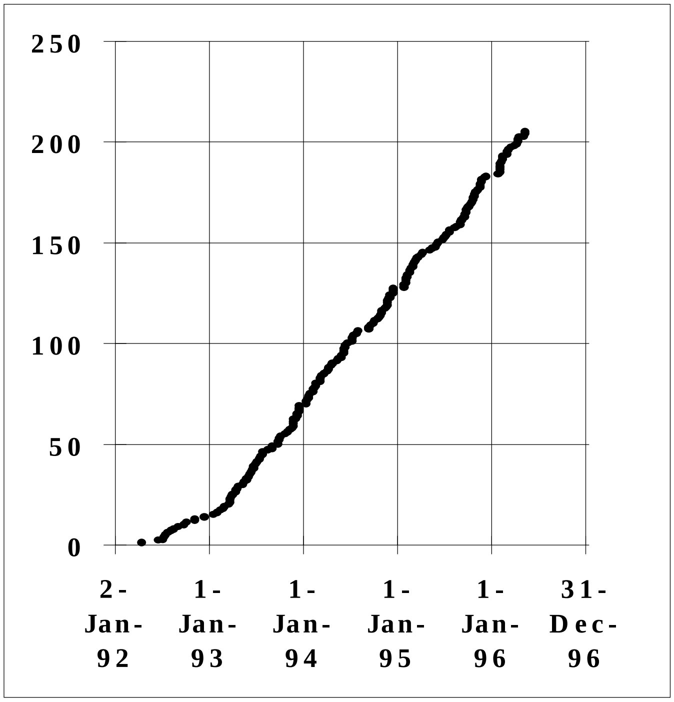

Fig. 6. Number of accepted cavities *vs.* time

One of the keys to the success of the project has been the availability at CERN of the necessary know-how and equipment for backup if the companies experienced any temporary disruption of the production. CERN was able to check procedures at any time and at any stage of production (chemical treatment, Nb-coating, high-purity water rinsing etc.) to determine where the problem originated. It is of the utmost importance that this system of CERN-based checks be maintained until the end of the LEP upgrading project.

It has been demonstrated (Fig. 7) that the Q-values of Nb-coated cavities are superior to those of bulk Nb for the same frequency and at the same temperature (4.5 K). It should be noted that this comparison is quite fair, since the cavities of both types were produced by the same company. Bulk Nb shows thermal quench, which is not the case for Nb/Cu, and it has to be emphasized that none of the 45 modules tested was limited by a thermal quench.

A further advantage of this technology is its economy: comparing the industrial costs of bulk Nb and Nb/Cu cavities, it can be concluded that the total cost of cavity production for the LEP upgrade was reduced by about 20%. The Nb sputter-coating technique could be applied for future machines for frequencies up to 800 MHz, with accelerating fields between 6 and 10 MV/m at 4.2-4.5 K. More than 80% of the industrially produced cavities for LEP2 had $Q \geq 2.5\cdot10^{9}$ at 8 MV/m (4.5 K).

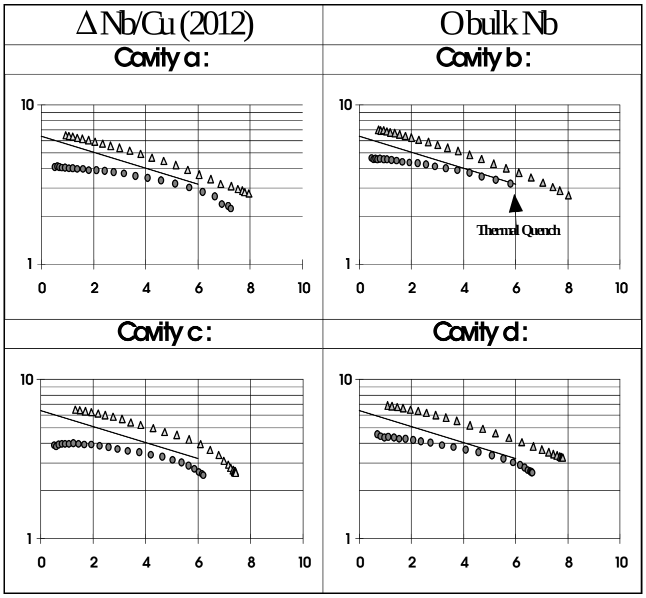

Fig. 7. Comparative performance of Nb bulk and Nb/Cu

Very encouraging results have also been obtained at CERN for a higher frequency (1.5 GHz) An accelerating field of 13 MV/m and low field Q-value of $Q > 10^{10}$ were achieved with a five-cell cavity at 1.8 K [5].

The success rate of production could probably be further increased by making some improvements in surface preparation (electropolishing the whole cavity or developing a new chemical treatment). In addition visual inspections could be replaced by more objective procedures. In order to avoid expensive and lengthy recovery operations it is very important, particularly in a real industrial environment, to establish correlations between fabrication steps and cavity performance.

I would like to stress that the new technology has attained sufficient maturity to make it attractive for future applications.

6 ACKNOWLEDGEMENTS

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