Industrial production of Superconducting niobium sputter coated copper cavities for LEP

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Abstract

We report on experience on the production of superconducting (SC) RF cavities for CERN's e^+e^- collider LEP by European industry. We give an account on a first phase during which technology was transferred to the firms. Then we analyse the series production of cavities in terms of RF test results, their performance and problems that turned up in between.

1. INTRODUCTION

CERN's e^+e^- collider LEP is actually being upgraded to centre of mass energies of 180 to 200 GeV (LEP200). The geometry chosen at CERN was a four cell cavity in the π accelerating mode with power and higher order mode (HOM) couplers located at the beam tubes [1]. The whole number of SC cavities will be 192, by which the total voltage of SC RF will be over 1600 MV. The first 12 cavities (prototypes) were produced by CERN and have been operated in LEP [2]. The next 20 (made from Nb sheet metal) have been fabricated by industry [3] and successfully undergone the acceptance tests at CERN.
The major part (160) of cavities is now being produced from copper and coated with niobium (NbCu cavities). In a first test of an individual cavity in a vertical cryostat at CERN the coating will be qualified before the cavity will be sent back to industry for assembly. We will report on these tests. Back in the companies, each of these cavities is equipped with a power coupler and two HOM couplers. Four of them are connected into a module, which is sent back to CERN for the final acceptance test [4].
The acceptance criteria for the coated cavity were defined as to a Q-value of $4 \cdot 10^9$ be obtained at 6 MV/m accelerating gradient and a temperature of the liquid He bath of 4.2 K.
Should the specified values not be met, the coating will be removed by an etching agent and a second coating will follow.
The companies to which the contract was awarded were Ansaldo in Genova (Italy), CERCA at Romans-sur-Isère (France) and Siemens at Bergisch-Gladbach (Germany). These firms had experience in producing SC magnets (Ansaldo), and SC cavities (CERCA and Siemens). However, they had not yet delivered SC cavities completely assembled ready for turn-key operation in an accelerator, as CERN has asked for. All three firms had experience in producing "high technology" elements, but none had experience in all relevant domains simultaneously, such as electron beam welding, ultra high vacuum technology, chemical cleaning, physical vapour deposition, and clean room and ultra pure water facilities.

2. PREPARATORY WORK

In order to have 160 cavities within two years time available at CERN one must accept eight cavities per month. With 2 tests necessary per accepted cavity (anticipated for the running-in phase of production) one must perform 16 RF tests per month or 4 RF tests per week. One RF test in a vertical position consists of taking the Q-value vs. gradient curve in the four different pass band modes, a maximum time of 24 hours of He processing (if needed), determining the BCS and residual surface resistance by pumping down the liquid helium (LHe) bath from 4.5 K to 2.5 K, and mapping the RF surface losses of the cavity. This procedure takes one week. Hence 4 cryostats have to be operated simultaneously.
The decision was taken to construct a vertical test facility in one of the large assembly halls of CERN (SM18). During construction of this facility, in the first half of 1991, we updated the existing SC cavity test area (used in the R&D program) by installing new RF and computer equipment and an automation of the LHe supply from a 6000 l LHe dewar being fed by a newly purchased 140 l/h He liquefier.
As from January, 1991, the transfer of know-how to industry was started and the prototype cavities were tested in the existing installation (more than 11000 l LHe were needed per week). Between September 1991 and July 1992, each firm had qualified itself by a pre-series production of two prototype cavities and then started the series production (Fig. 1).

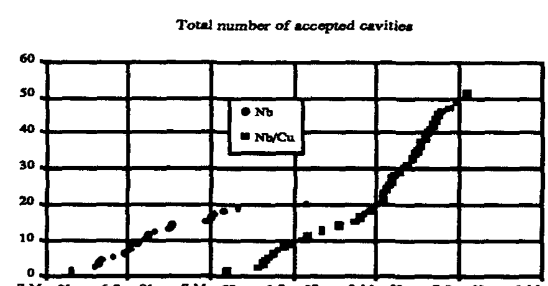

Fig. 1: Accumulated number of accepted cavities of the NbCu type vs. time (and similarly for the niobium sheet type at the left).

3. THE SERIES PRODUCTION

3.1 Suppression of defects

One problem we encountered were defects on the niobium layer (Fig. 2) detected by temperature mapping [5]. In the majority of cases they could be associated to a region of poor adherence of the niobium coating of less than 1 mm size ("blistering"). Very often the copper underneath was contaminated by particulate matter or stains. An investigation revealed a damage layer from lamination deep inside the copper sheet at 80 to 120 µm [6]. This was just the depth to which the damage layer was removed by chemical etching.

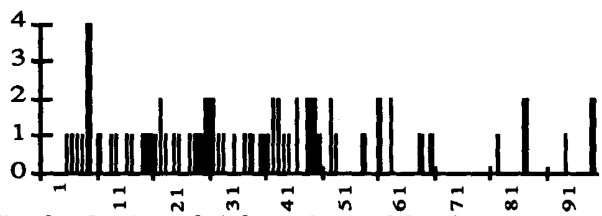

Fig. 2: Number of defects detected by "temperature-mapping" vs. consecutive test number. A defect is defined as inducing a temperature signal $\Delta T \geq 100$ mK.

Therefore we applied electropolishing in two steps, which allowed a controlled removal of the copper to a larger depth (120 µm) and gave a more shiny surface. In between these steps the surface was visually inspected, and surface flaws were removed, if necessary. The number of defects were gradually reduced (Fig. 2), and the ratio of accepted to coated cavities increased (Fig. 3).

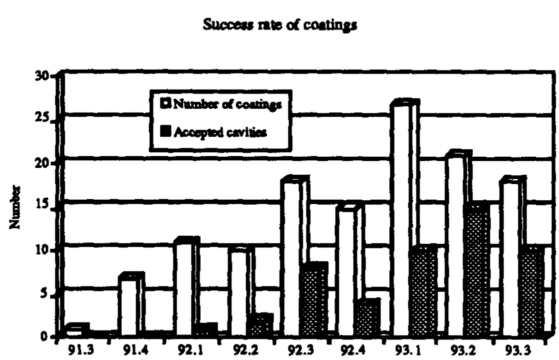

Fig. 3: Number of accepted cavities compared to number of coatings performed (per three months).

After this modification of the recipe, in one firm the rejection rate of cavities (for the first coating) decreased to 15 % due to reasons not understood right from the beginning (although the same cavities after being coated twice could in nearly all cases be accepted). In another firm, however, it remained high at about 85 %.
However, at the first company, for the first coating, in a systematic way, the BCS Q-value was lower (~$8 \cdot 10^9$), the dependence of the Q-value on a static external magnetic field was larger (though much less than for niobium sheet, cf. Fig. 8), and the losses were concentrated in the middle cells. This observation allowed to trace back that the bakeout after electropolishing before coating was short (20 h), though within specifications, and the cool down was fast (1 h). The company has modified the procedure and the first RF tests indicate better results. Further tests are needed as confirmation. Anyhow, such cavities, which showed poor results after being coated for the first time, could be accepted after a second coating under otherwise similar conditions.

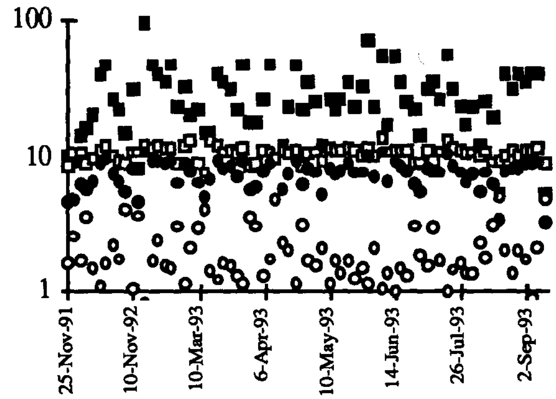

Fig. 4: Evolution of parameters of the niobium coating vs. date (from top to bottom are plotted: Q_{res} [10^9], Q_{BCS} [10^9], Q(E_{acc} -> 0 MV/m) [10^9], $\Delta R_s/\Delta B$ [nΩ/mT].

The parameters of the Nb layer, as the BCS Q-value at 4.2 K, remained, apart from these exceptional cases, remarkable constant in the course of the production. The residual Q-value Q_{res} and the slope $\Delta R_s/\Delta B$ of the average surface resistance vs. RF magnetic field amplitude scattered, as shown in Fig. 4.

3.2 Water rinsing

A second problem we often encountered at the beginning, was the generation of an electron dark current by field emission from sites in the high electric field region in the cavity. These spurious electrons extract energy from the electromagnetic field inside the cavity and transfer it to the cavity wall (electron loading), thus increasing the losses. There exists a body of evidence on the reduction of electron loading after rinsing with ultra pure water [7, 8]. Therefore, the companies improved their water installations. Resistivity, total organic carbon (TOC), and bacteria content are more regularly and more carefully controlled than before. Filters were installed at the point of use. The mass flow and pressure were held at a constant value. The results are shown in fig. 5. The number of events where a cavity was conditioned under low He gas pressure ("He processing"), sometimes inefficient, is considerably reduced in the course of production.

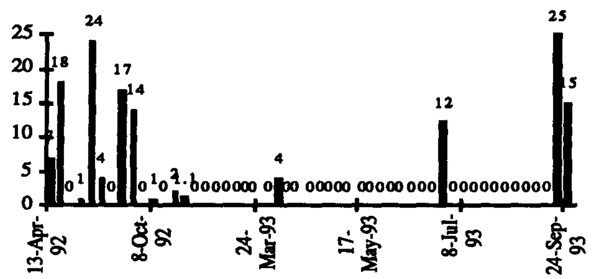

Fig. 5: Time of application of He processing (h) in the course of series production of SC cavities.

Rinsing the cavity with water under low and high pressure [9] was also applied to recuperate cavities which had a low Q-value or/and which were limited by electron dark current activity (Fig. 6).

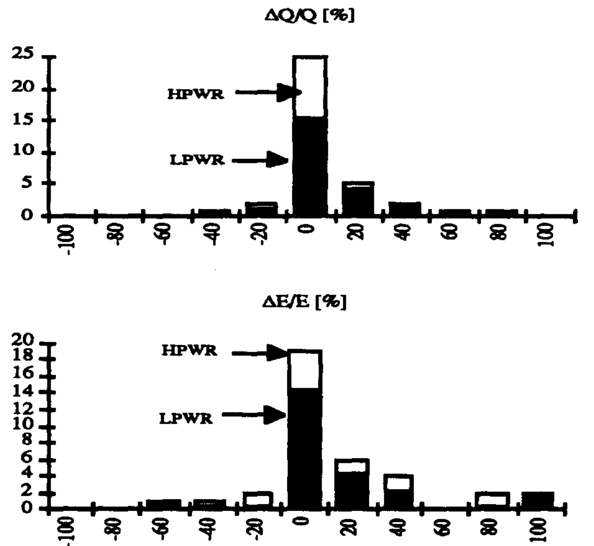

Fig. 6: Number of improvements in % of low field Q-value and maximum accelerating gradient (at 200 W RF power available) after low (LPWR) and high pressure water rinsing (HPWR).

There is an indication that rinsing with water under low pressure is more efficient in increasing the low field Q-value, and rinsing with water under high pressure is more efficient in removing electron loading. 24 per cent of cavities, otherwise to be rejected, could be accepted after an additional water rinsing. All three companies have up till now produced more than 50 cavities in total, about one third of the project.

3.3 Results of RF tests

The number of RF tests necessary before acceptance varies between 2 and 3. The results are remarkably similar for all three companies. In Fig. 7 are shown the Q vs. accelerating gradient curve for three cavities from each of the companies, one with the lowest Q-value at 6 MV/m, one with the largest Q-value at 6 MV/m and one with the largest accelerating gradient E_{acc}.

It should be noted, that for reasons of availability of test facilities the curve with the largest Q-value at 6 MV/m has been obtained at 4.2 K, whereas the others have been measured at 4.5 K. It turned out that this temperature increase may decrease the Q-value by about 15 %, independent of E_{acc}, due to the temperature dependent slope of Q vs. E_{acc} (non quadratic loss [10]).

3.4 Organisation of quality control

It is evident that a close feedback of information from RF tests at CERN to the production crew at the companies is mandatory. CERN personal has spent about 25 % of its working time on the production site.

Each company is visited by two people from CERN at least once per month. The companies have an internal quality control service to perform internal audits, which is detached from the production crew.

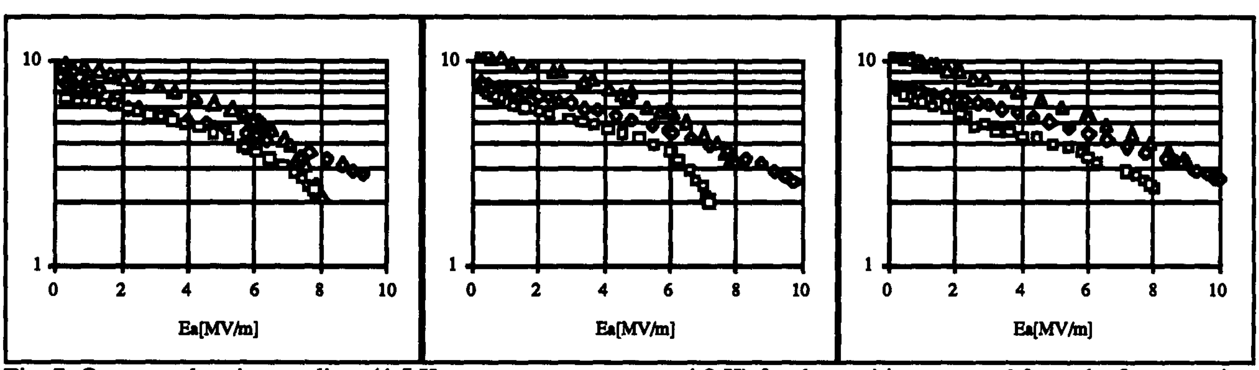

Fig. 7: Q vs. accelerating gradient (4.5 K, except upper curve at 4.2 K) for the cavities accepted from the 3 companies: three typical curves are selected, one with the largest Q-value at 6 MV/m accelerating gradient, one with the lowest (but still acceptable) one at the same gradient, and one with the largest accelerating gradient (for ~250 W RF power available).

3.5 Magnetic field dependence of Q-value

One might be concerned whether the coating will keep its insensitivity to static magnetic fields compared to niobium, when the coating is improving in terms of RF loss. Therefore we equipped one cryostat (which was not shielded against a static magnetic field) with an arrangement of coils to compensate (or increase) the ambient magnetic field. In Fig. 8 the average surface resistance (280 Ω/Q[10^9]) is plotted for zero field gradient and at 6 MV/m for three different cavities, the first two ones with good RF results, and the last one with poor. It turned out that the former exhibited less sensitivity to a static magnetic field (30 nΩ/mT for E_{acc} -> 0 MV/m) than the latter. At any rate, the sensitivity is much less than for niobium sheet (1500 nΩ/mT for E_{acc} -> 0 MV/m).
This might be an indication that DC and RF induced magnetic RF loss are closely related [10].

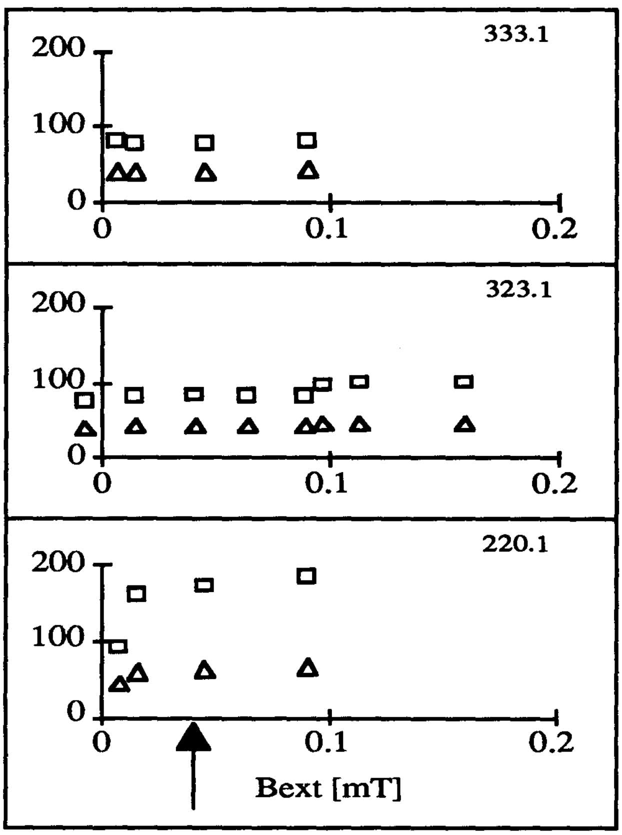

Fig. 8: Average surface resistance (lower: at low gradient and upper: at 6 MV/m) of a cavity exposed to a static magnetic field perpendicular to its axis. The arrow indicates the ambient field near the cryostat.

4. CONCLUSION

Series production of NbCu cavities for LEP is underway, about one third (51) of the cavities being accepted. Three companies have proved able to produce cavities with a rate of one per week each in a reproducible way. Though the parameter space for the coating is narrow, the RF relevant properties of the superconductor have remained remarkably constant throughout the hitherto accomplished production. The static magnetic field dependence of the surface resistance turned out to be a useful diagnostic tool. A shiny copper surface, where defects can easily be localised and removed, and which is processed dustfree and well baked prior to coating, is essential for a good RF performance. A considerable number of cavities has been accepted after another water rinsing (under low and/or high pressure).

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