A REVIEW OF THE NIOBIUM ON COPPER SPUTTERING TECHNOLOGY FOR SUPERCONDUCTING RF CAVITIES

S. Calatroni*, CERN, 1211 Geneva 23, Switzerland

Abstract
This paper aims at giving a historical overview of the niobium on copper sputtering technology for RF cavities and its main advantages and disadvantages with respect to bulk niobium cavities. Some highlights of the present understanding will be given and some directions for further development will be discussed.

THE LEP CAVITIES

The development of the deposition of Nb thin films onto Cu cavities with the sputtering technique has started at CERN in 1980 [1], the target application being of course the LEP collider, operating at 352 MHz. At that time, the main reasons for undertaking such an approach were the following: a) Better thermal stability (resistance to “quench”) thanks to the much higher thermal conductivity of the OFE copper substrate compared to the superconducting niobium; b) Reduced material cost; c) Possibility of applying high Tc coatings (NbTiN, V3Si, Nb3Sn, HTS…).

After first studies using the diode sputtering technique, the magnetron sputtering technique was adopted in 1985. This technique, where a magnetic field is superposed (crossed) to the electric field thus increasing the ionization rate, allows much lower sputtering pressure and cathode voltage [2] and is highly beneficial in terms of film purity, structure and overall quality. This allowed a significant breakthrough in performance. It should be noted that Nb bulk cavities were produced in the eighties starting from sheets having RRR of 40, resulting in a very limited thermal conductivity at cryogenic temperatures. Typical performance of bulk cavities at 500 MHz and 4.2 K was $Q \approx 2.5 \times 10^9$ ($\approx 100 \, \Omega$) at low field, approximately decreasing by a factor 2 at fields of the order of 10 MV/m, where quenching usually happened. Film cavities immediately showed a higher $Q$ at low field ($\sim 3.5 \times 10^9$) than bulk ones (Fig. 1). This is due to a lower BCS surface resistance, in turn related to a normal state electrical resistivity close to the theoretical optimum (Fig. 2). The $Q$ factor decreased more strongly with field compared to bulk Nb due to the residual component, but remained comparable to the bulk Nb at field levels of interest for LEP. In those days, accuracy and cleanliness of surface preparation were not as accurate as can be done today, and it was rare that the accelerating field reached values higher than 8 MV/m. The goal of suppressing quenches was also successfully attained.

A further important development was the establishment of an adequate chemical polishing procedure in order to improve the copper surface smoothness and promote film adhesion, compared to the simple acid etching used previously. Both developments were first applied to 500 MHz cavities and then chosen for the production of the 352 MHz prototype cavities for LEP. The results showed an even better performance compared to Nb bulk (Fig. 3). Eight pre-series 4-cell cavities for LEP were built at CERN, the remaining 264 were made by three European industrial suppliers.

LEP was operated at 4.5 K. At that temperature, the BCS component and the residual component of the surface resistance have roughly the same magnitude at 352 MHz, i.e. about 20 nΩ. Approaching 0 K the BCS surface resistance vanishes exponentially and the residual term remains dominant. This is of a comparable order of magnitude at zero-field between sputtered films and bulk, but has a stronger increase with field in the case of films, which thus show a “slope” in $Q(E)$ plots.

Films showed also an unexpected advantage, in that

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*sergio.calatroni@cern.ch
their surface resistance is almost insensitive to the Earth’s magnetic field. As an order of magnitude the effect is 100 nΩ/Gauss of external magnetic field for bulk Nb, and only 1 nΩ/Gauss for films. This allows for the fabrication of much simpler and cheaper cryostats without the need of complex magnetic shielding of cavities.

R&D AFTER LEP

The same Nb/Cu magnetron sputtering technology has been applied for the LHC cavities. Sixteen cavities (single cell, 400 MHz) are installed in the LHC. No particular developments were done for this project, apart from the obvious adaptation of the technique to a different geometry. Nevertheless, the progress in surface preparation and the overall improvement in cleanliness allowed exceeding the specification values, and reaching routinely fields in excess of 10 MV/m. It was rather clear from this experience that the electron-field-emission limitation to the maximum achievable accelerating field was a problem of cleanliness and accuracy of the final water rinsing, and no intrinsic limitation was inherent to the films. This was in line with what observed in parallel by the bulk-Nb community.

After the developments for the LHC cavities, two main lines of research have been pursued at CERN starting from 1995. The first one was devoted to applying the magnetron sputtering technology to accelerating cavities of rather low frequency for particles of \( \beta < 1 \) (for proton linear accelerators). This topic and the associated R&D are discussed extensively in [7] and [8]. The second line was devoted to studying the ultimate performance that can be reached with the magnetron technology in terms of Q and accelerating field at 1.7 K in cavities for electron linear accelerators.

**Ultimate performance in \( \beta=1 \) cavities**

The search for ultimate performance was carried out on single-cell 1.5 GHz resonators after first encouraging results obtained by a CERN-CEA/Saclay collaboration [9], and was essentially focussed until 1999 in identifying whether the standard superconducting quantities have any influence on the residual resistance. More than 200 test coatings have been carried out using adapted magnetron coating technology, and completely characterized in RF. It turns out that the residual surface resistance is not at all correlated with the measurable superconducting quantities [4]. This result was supported by a large wealth of material studies carried out on samples, such as SEM, TEM, XRD and composition analyses, as well as the classical superconductivity characterizations.

Comfotred from this result, the work was focussed from 1999 onwards into improving the quality of the copper surface preparation, by pioneering the electropolishing of the full cavity, in order to have the smoothest possible surface. Previous results with chemical polishing and different techniques for cavity manufacturing (hydroforming, half-cell welding, full-cavity spinning, electroforming) already gave indications that this was the right road for the improvement of surface resistance [10, 11]. In parallel, the high-pressure water rinsing facility at CERN was improved and optimised for the treatment of these cavities. The outcome of these efforts proved to be fruitful [12] as illustrated in Fig. 4.

However, even if the performance was greatly improved from the LEP-era values, the “slope” of the residual resistance was still present. This was a limit to

![Figure 3: Performance of prototype LEP 352 MHz cavities, bulk Nb and Nb/Cu. (From [6]).](image)

![Figure 4: State-of-the art performance of Nb/Cu cavities at 1.7 K and 1500 MHz (adapted from [12]).](image)
the achievable maximum field because of the high RF power dissipation, saturating the available power amplifiers, and sometimes leading to fast helium boil-off in the cryostats. A maximum accelerating field of 28 MV/m could nevertheless be attained in an ad-hoc experiment in a large volume cryostat. Phenomena like quenching or field emission never occurred on properly treated Nb/Cu cavities. Moreover, the large world community working on Nb-bulk cavities was proving at the same time that the maximum field is function only of the surface cleanliness (below the superconductor critical field), and that the performance could be extended to unprecedented high fields thanks to the fact that bulk Nb does not show a similar “slope” [13] (incidentally, the same HPWR facility developed for Nb/Cu cavities has been used for the first European high-quality fully electropolished TESLA-type Nb-bulk cavities).

Search for the origin of the residual resistance

The activity has next been focussed in finding the possible causes of the “slope”. One should underline first that some models predict that such a “slope” is inherent in films because of the limited electron mean free path compared to bulk. This should manifest either in a reduction of $H_c$ and thus nucleation of (Abrikosov) fluxons [14] in a rather low RF field, effect possibly enhanced by demagnetization due to surface roughness. Or it could manifest itself in a depression of the superconducting gap due to a reduction of the critical superfluid velocity [15], this transforming directly in an increase of the BCS surface resistance. Both phenomena do clearly happen in films, however it is difficult to estimate a priori their importance.

Much effort has been devoted to identifying whether the hydrogen trapped in the film was a possible cause of the “slope”, since this has always been a primary source of losses in bulk Nb cavities. The quantity of hydrogen contained in the films, depending on the coating procedure, has been measured accurately, as well as its binding state. The largest possible sources, i.e. the Nb cathode and the copper substrate, have also been characterised fully and suitable means to reduce their hydrogen content have been found [16]. Further ways of reducing the hydrogen content of films by means of NEGs have been devised. Unfortunately hydrogen reduction was not effective [17] for reducing the “slope”.

Further efforts have been devoted in determining whether the Nb/Cu interface introduces a thermal barrier, such that the “slope” would be produced by a thermal runaway effect [18]. Accurate measurements on samples showed that Nb coated specimens have the same thermal conductivity (in the direction normal to the surface) at 1.7 K as the naked substrate, be it Cu or Nb [17].

A third line of thought lies in further optimising the roughness and the structure of the film, having in mind the flux penetration mechanism mentioned before. Copper electropolishing was put under firm control by elaborated numerical simulations and chemical analyses, and it is not believed that this could be optimised any further [17]. The roughness of the substrate has strong influence on the roughness of the film, and self-shadowing effects during film growth may lead to poorly connected Nb film grains, possibly enhanced by a non-normal angle of incidence. Granularity effects have always been seen as a major source of trouble in literature, either because of possible losses in weak-links [19], or because of easier penetration of (Josephson) fluxons [14].

This leads naturally to the idea of introducing important changes to the coating technique, with the aim of optimising the smoothness of the films at the crystal grain scale and minimising the density of defects. Several developments are being pursued at present in various Laboratories.

FUTURE RESEARCH AND DEVELOPMENT

A first simple step towards improving the film quality is by adding a bias to the classical magnetron configuration, for having a Kr ion bombardment during film growth. This should produce smoother films and has been tested at CERN. First results did not show however significant changes in RF performance.

A further possibility is to create the film using Nb ions, instead of neutrals such as in sputtering, directed to the substrate by a bias thereby allowing conformal deposition with a normal angle of incidence everywhere and thus suppress self-shadowing. The most promising techniques have been selected by different Laboratories and are under development or being tested. Cathodic arc [20] and ECR post-ionisation [21] of evaporated Nb will be discussed elsewhere in this Workshop Proceedings. CERN developments are concentrated on High Power Pulsed Magnetron Sputtering (HPPMS).

High Power Pulsed Magnetron Sputtering (HPPMS)

HPPMS is an evolution of the magnetron technique which relies on ~100 µs high-voltage pulses of the order of ~1 kV, compared to the ~300 V of the standard DC magnetron process [22]. During the pulse a very large power density is deposited onto the target, of the order of a few kW/cm² compared to a few 10s of W/cm² of the standard DC process, producing a highly dense plasma in which a fraction of the Nb atoms is ionised, attaining values close to 100% in the best cases [23]. These ions can in turn be attracted to the substrate with a suitable bias to produce the coating. The repetition rate of the pulses should be kept at a few 100s Hz in order to keep the same average power and coating rate as in the equivalent DC sputtering process. A further advantage of the technique lies in the fact that no hardware modifications are required to a standard DC biased magnetron system, except for the obvious replacement of the power supply.

First experiments at CERN have been carried out in a classical planar magnetron system using a low repetition rate power supply (surplus from old pulsed LINAC
magnets). The implementation of the technique is fairly smooth and coatings can be obtained from the first run. Fig. 5 illustrates typical pulse values obtained in a test run. It should be underlined that these depend greatly on the power supply adopted and that the one used was clearly not optimal (repetition rate of 1 Hz) and its specifications underrated. The sputtering parameters are however in the good ballpark, and the films obtained have RRR and Tc similar to films produced with the same coating system using DC sputtering [24]. There were however no significant changes in the film morphology, probably because of an insufficient ion fraction in the coating, estimated at 1% from the ratio of sputter and bias current, assuming a sputtering yield of 1.

A drawback encountered in the process was the generation of arcs, which were not quenched by adequate circuitry within the power supply and even resulted in cathode damage. This appears to be the major obstacle in the correct implementation of the HPPMS coating technique [25]. A suitable power supply, with higher power, faster repetition rate and a sophisticated arc-suppression circuit is being designed at CERN, in collaboration with HES-SO (Yverdon, Switzerland) and is scheduled for completion by end 2007. A decision on its construction will then be taken depending on funding, on market availability of similar items, and of course on the CERN strategic interest.

CONCLUSIONS AND OUTLOOK

In the opinion of many authors, niobium films have not yet achieved their possible ultimate performance, contrary to what has been obtained with niobium sheet cavities, and this hinders at present their use for electron linacs although their cost is far inferior. The understanding of the physics behind their present limitations is thus of high importance, both scientifically and technologically. Several novel developments in the coating technique are under study which, on the grounds of the present understanding, may produce an important leap forward.

REFERENCES