REVIEW OF FABRICATION OF SC CAVITY STRUCTURES

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Abstract

The search for higher and higher accelerating fields with low rf losses, plus the need of know-how transfer from scientific laboratories to firms for industrial cavity production, have contributed to the establishment of fabrication technology standards. Over years of research both on high beta and on low beta superconducting resonators, various criteria improving resonator rf performances has been codified as guide-lines or canons in the fabrication process. However, the simple transfer of the standard cavity fabrication technology developed so far, is no longer sufficient for the new generation machines. Not only the progressive achievement of higher accelerating fields, but also the drastic reduction in resonator production time and costs (K$ per MV/m) is compulsorily for the feasibility of more and more powerful accelerators. This is the motivation under the research toward simpler and cheaper fabrication techniques as for instance seamless cavities. The paper reviews the status of those new forming techniques under development in several laboratories, as hydroforming, spinning, backextrusion or superconductor/normal metal coated cavities suitable for prototype fabrication and at least in principle, considerable for mass scale production.

1 INTRODUCTION

About ten years ago, the Argonne National Laboratories under the chairmanship of K. Shepard hosted the third Workshop on RF Superconductivity [1]. In this occasion everybody involved in the superconducting cavity field was proud to show his last and best result. At that time the LEP design value consisted in a gradient of 5MV/m at a Q-value of 3e+09 and the three industries involved in the Nb/Cu sputtered resonator production did not yet even start to acquire know-how. D. Proch in a talk on SC cavities in Storage Ring Beam Tests, was reporting values of the accelerating field values ranging from 1.9 MV/m to 6.5 MV/m [2]. The maximum accelerating field reported for the TRISTAN 500 MHz 5-cells was lower did not overcome the 10 MV/m [3], while G. Mueller reported even fields up to 24 MV/m but on a Nb single cell and at 3 GHz [4].

About 10 years later again under the ANL organization, the 98 LINAC conference will see the presentation of results such as the 30 MV/m in the high 1e+9 - low 1e+10 range in horizontal test for some TTF 1.3 GHz 9-cell resonators coming from the industrial production [5] or such as the 40 MV/m at a Q of 1e+10 obtained by K. Saito on a 1.3 GHz Niobium single cell [6]. The superconducting resonator fabrication technology has made great strides, improving the manufacture standards, and importing the know-how of the ultra-clean from the neighbouring field of semiconductors. In parallel to the traditional technology of Electron Beam (EB) welded cavities, already three laboratories are able to form seamless Niobium cavities of the TESLA shape [7-9]. Besides to whom is depositing Niobium onto Copper, who reinforces Niobium with Copper is also coming to the fore [10]. Last, the traditional separation between "low beta people" and "high beta people" is becoming weaker and weaker, since middle beta cavities are becoming a subject more and more investigated.

2 THE MOST SAFE APPROACH: THE BULK NIOBIUM TECHNOLOGY

It is not by accident that TTF is installing bulk Niobium 9-cell cavities. The TESLA goal is 25 MV/m at a Q-value of 5e+09 and the bulk Niobium technology is the only one capable to satisfy this requirement at industrial level in the shortest possible time. This does not mean no room for the Nb/Cu sputtering approach, but only that an eventual R&D for sputtered nine-cells has compulsorily much longer R&D times. On the other side it must be own that the traditional approach to EB weld half cells, both for material and for manufacture, has been convenient for the TJNAF 1.5 GHz 5-cell production, but it is is definitely too expensive for a possible mass production of 20,000 cavities, as in the TESLA Project.

The traditional fabrication approach for beta 1 resonators consists in forming the cavity cups by spinning or preferably by deep-drawing. The cup edge are trimmed by machining. The possible variation in wall thickness due to the mechanical tolerances of the drawing tool can influence the geometry so the resonant frequency (df/dl_{9cell} = 300 KHz/mm). Pad rubber forming has been proven to show the best reproducibility [11]. Facing the cups is the most crucial operation and it is performed on a rotating machine: any misalignment will certainly result in cracks along the EB weld. The thickness of the lip to weld is much smaller than the equator diameter, moreover the heated zone will thermically expand respect the cold one. This can seldom result into a trivial problem especially occurring when going to weld cups drawn from textured slabs: it is not said that the ending point of the weld will necessarily coincide with the point from where the EB started. However, nowadays the Niobium EB weld technology for SC cavities is well-established and has been transferred with full success from research laboratories to industrial partners. Prior to the welding, cups and beampipes are chemically treated by a Buffered Chemical Polishing (BCP) $HF/HNO_3/H_3PO_4$ 1/1/2 in volume, followed by ultraclean water rinsing and handling in clean environment. The Niobium is oxidized by the nitric acid, then the oxydes if transformed in fluoride thanks to the high electronic affinity of fluorine. The Niobium fluoride is a salt highly soluble in water. The phosphoric acid mainly works as moderator.

After welding the cavity undergoes two main steps: titanified at 1400 C in UHV and chemically etched in a virgin 1/1/2 bath, then Rinsed with ultrapure water under High Pressure (HPR) usually at 100 bar.

Besides this elementary recipe some other fabrication steps have been found necessary in order to achieve voltages in the 20-30 MV/m regime and are clearly reported by Matheisen in his paper about the "Improvements on standard Fabrication methods" [11]. They can be listed in the following:

1) Since the Niobium ingot is Electron Beam melted in the UHV oven, already it is necessary to exercise a strict control that ultra clean conditions are respected. The use of a furnace seldom used for melting other elements is risky.

2) Rolling of sheets from ingot is not a less crucial step, since microparticles produced during rolling are pressed and embedded into the bulk.

3) The defect diagnostics of Niobium slabs by eddy current scanning provides a more accurate selection of sheets. It has been seen that by this method, the quench limitations can be sorted out in a very early step of the production.

4) The control of the BCP temperature kept lower than 15 C, in order to avoid hydrogen charging of Niobium.

5) The adoption of a wiggled beam with 50% penetration on the first welding turn, followed by a wiggled full penetration beam, since this sequence is less sensitive to fabrication tolerances.

6) The vacuum in the welding furnace must be lower than 5e-5 mbar, depending the Residual Resistivity Ratio (RRR) value on the chamber residual pressure.

Besides to this DESY experience seems to advice that quenches below 30 MV/m in multicell structures can be avoided by a strict application of cleanroom techniques followed by postpurification of Niobium.

Recently K. Saito has perturbed the common beliefs about the Niobium chemical treatment, sustaining the superiority of electropolishing over chemical polishing on high gradients [6]. The problem must be encountered in deeper detail, however the fact remains that he has reached 40 MV/m at 1e+10 on a 100 micron electropolished cavity. Electrochemical-mechanical buffing has been also proposed in the framework of a KEK-Mitsubishi collaboration in order to get the smoothest Niobium surfaces. The combination of mechanical polishing and electrochemical polishing is a well-known technique adopted for silicon wafer polishing.

Following the above mentioned basic fabrication rules, bulk Niobium and the related EB welding is a paying technology also for low beta cavities. Facco at LNL [12] has produced and recently installed 80 MHz Quarter Wave Resonators in the low beta section of ALPI. An average accelerating field of 7 MV/m at 7 Watt has been reached after HPR. In place of an electronic fast tuner a mechanical dissipator is inserted into the resonator shaft, in order to damp vibrations caused by the environment. An accelerating field of 5 MV/m at 7 Watt has been achieved in the bulk Niobium QWR prototype developed at NSC in New Delhi [13].

A masterpiece of EB welding is however the bulk Niobium RFQ for the PIAVE Injector of LNL [14], that in its complexity is up to now the most difficult bulk Niobium SC resonator ever built. Machining of the electrodes, Extrusion of the Cylinder on the back of the Electrodes, deep drawing of the stems, stiffening of the external tank by titanium liners, EB welding, and BCP are all operations that must be done within a few hundreds of tolerance.

Last we wish to mention in this paragraph the experiments conducted at Wuppertal with Nb_3Sn, since Nb_3Sn was prepared by vapour diffusion onto a bulk Niobium cavity [15]. The purpose consists in operating at 4.2 K instead than at 1.8 K, due to the higher critical temperature of the compound. At 4.2 the cavity arrived up to 30 MV/m of peak field; moreover at low field the Q-value was a factor 2 higher that the value of the Niobium substrate at 2 K. A similar slope of Q versus field is found also for NbN thermally diffused Niobium cavities [16]. The investigation carried on this material however is some order of magnitude lower than the efforts paied on bulk Niobium cavities. However the problems related to such multicompositional material are much more complex than those of Niobium.

3 ALL NIOBIUM DEEPER THAN A FEW LONDON PENETRATION DEPTHS IS UNNEEDED

The rf loss mechanism in a SC cavity is confined within the first 5,000 Å, approximately ten times the London penetration depth. That means that all the Niobium deeper is there only for providing mechanical rigidity. Moreover Niobium is neither a good thermal conductor. The first Copper-superconductor resonators were done by electroplating a Lead film. Lead has a critical magnetic field of only 500 G at 4.2, moreover its porosity and its density is dramatically sensitive to the action of moderators mixed into the plating solution. Without the right moderator indeed Lead would grow according to a dentritic structure. The main problem of surface instability has been solved [17]. Under the electrodeposition of Lead there is no black magic. All the black or yellowish spots people found after deposition were caused from residuals of the fluoborate plating solution coming from an imperfect rinsing of the surface, or from the dehydratation of Lead hydroxyde.

A very nice material to play with is the Japanese Niobium clad Copper slabs, since in RF it behaves as Niobium, while mechanically is workable as Copper. Both the Argonne National Laboratory Split Loops [18] and interdigital QWRs [19-20], and the JAERI cavities have only the external enclosure in Nb-Cu, being the loop or the shaft instead in bulk niobium. Split Loops are cavities that by now have been tested for a very long time since two machines have been built in ANL and Stony Brook respectively. With interdigital also "there are no surprises", since they are operational from '93. Considerably high performances were achieved by JAERI niobium clad copper QWRs. Maximum accelerating fields are normally higher than 7 MV/m, even up to 13 MV/m, that for such a resonator geometry means an electric peak field of 60 MV/m and a magnetic peak field of about 1000 G.

The sputtering of high quality Niobium films onto OFHC Copper cavities has been invented at CERN by C. Benvenuti and it has been successfully applied to LEP cavities. After the successful transfer to the European Industry, This technology has been recognized as a valid and in some cases superior alternative to bulk Niobium resonators. Almost concluded the 352 MHz production CERN is dedicating not little effort in order to understand the mechanism preventing the achievement of theoretical performances. Smaller size cavities such as the 1.5 GHz monocells are very suitable for this purpose. The coating method is based on a Cylindrical magnetron configuration: in a noble gas atmosphere, generally argon, at a pressure of the order of 1e-03 mbar, a potential difference is established between the central cathode and the grounded cavity. The electrical current of the glow discharge is stabilized by a permanent magnet internal to the cathode. The sputtering temperature takes place at 150 C and the coating thickness is 1.5 microns obtained in 15 minutes of treatment. The films have a RRR of 11, the average grain size is around 1000 Å [21]. It is worthwhile to report that the Copper substrate plays a crucial role for the film growth. All Nb films sputtered onto spun substrates have lower losses and Q-slope than those on hydroformed substrates. The role of sputtering parameters on RF performances are investigated as well as the relevance of physical mechanisms acting on BCS and Residual Losses.

Nb sputtering onto Copper has been applied also to low beta cavities as QWRs at Legnaro National Laboratories The first cryostat with sputtered cavities was already installed in 1995 on the ALPI beamline [22]. The average field was of 4 MV/m. Subsequently last year these four cavities were substituted with other four sustaining an average field of 6 MV/m at 7 Watt. In parallel it has started the operation of resputtering with Niobium the old Lead electroplated QWR in the ALPI middle beta section. The average field achieved with the first four resonators is of 4 MV/m. The sputtering configuration chosen at LNL was that of a DC Biased Diode, because it is the simplest to operate. A DC cylindrical magnetron sputtering instead is the configuration designed and built at the Australian National University [23]. All the needed investigation of correlation of the deposition parameters with the superconducting properties of the films has been carried out; the subsequent phase of sputtering onto the real Copper cavity is under investigation.

Sputtering opens new roads to superconducting cavities as the one of NbTiN films onto Copper. Some investigation has been carried on at CERN and at Saclay, but as for Nb_3Sn the problems to solve are hugely more complex than those under Niobium, but up to now they have been faced with hugely less people and investments.

A totally new solution in the Nb/Cu framework has been recently proposed by the Orsay group [10]. Thin Niobium cavities are Copper reinforced outside by Copper Plasma spray. A series of 3 GHz cavities has been fabricated by deep drawing and EB welding using 40 RRR Niobium sheets of 0.5 mm thickness. The cavities were heat treated at 1200°C with a titanium getter before Cu plasma spray. The first two tested cavities have a Q in the range 10^9 at 1.8 K and are limited by quench at field values around 15 MV/m. Taking benefit from the thermal conductivity and porosity of the sprayed copper layer (resulting in an increase of the heat transfer surface in superfluid helium), the quench fields measured before and after Cu plasma spraying are the same. Tests with high purity Niobium and at 1.3 GHz are in programme.

4 SEAMLESS CAVITIES: A WAY TO REDUCE FABRICATION TIME AND SAVE MONEY

Even not mentioning that the equatorial weld is the main source of defects, whenever 20,000 cavities will be done it is compulsory to conceive a fabrication method able to output at least one ninecell per hour. A few laboratories are mainly involved in this search.

1) At LNL the author has succeeded in cold forming both Copper and Niobium multicells by spinning a simple circular blank onto a collapsible mandrel [7]. The strong advantage of this method lays in the total absence of intermediate annealings. Moreover the method does not regard of the possible ununiformity and texture of the starting material, since during spinning all the material is mixed up again. Spun cavities have been sent to CERN, DESY, TJNAF and to KEK for characterization. CERN has proved that spun copper monocells are superior to hydroformed ones, because of lower losses and lower Q-slope. Accelerating fields up to 25 MV/m have been measured at DESY on 1.3 GHz Niobium monocells, while 28 MV/m has been achieved on a 1.5 GHz Niobium monocell by P. Kneisel. Niobium fivecells have been already successfully spun and are waiting for characterization. Clad Nb/Cu slabs were also spun in the framework of a LNL-KEK collaboration. Low RRR Niobium has been adopted for first test, however up to now no positive result has been found yet, since the cavity annealing after forming seems to open crack in Niobium. According the author, however this is a problem easily solvable when spinning a thicker slabs instead than a rolled blank.

2) At DESY a 1.3 GHz Niobium monocell has been successfully hydroformed from a seamless tube jacketed into a steel matrix [8]. The steel was removed chemically and after a preliminary chemistry, the cavity reached already 14 MV/m in range 1e+10.

3) At Saclay, C. Antoine succeeded too in hydroforming a Niobium single cell. Two intermediate annealings were applied, but what is surprising is that the Niobium was

very poor in RRR, nevertheless the cavity reached 18 MV/m [9].

4) Seamless Copper cavities were produced by explosive forming in the framework of a KEK-Toshiba collaboration, that however in recent times is evaluating the possibility to combine explosive forming with hydroforming [24].

5) Copper Electroforming is instead under investigation at CERN [25] and at Protvino [26].

5 THE NEW ARRIVALS: THE MIDDLE BETA CAVITIES

It is probable that middle beta cavities will play the leading role in the next future. In this framework Los Alamos National Laboratories already fabricated 0.48 and 0.64 beta cavities standing over 1e+09 up to 40 MV/m of peak field [27].

The spoke resonators [28] proposed by Shepard and Delayen are also structures over which already a certain amount of work has been done. New structures as reentrant cavities [29] or shorter QWRs are also suitable for being considered. However besides to new structures also new materials should be investigated. For high intensity machines Copper for instance is not the best material, because of the possible activation. The sputtering onto Alluminum or onto Graphite with buffer layers would be worthy of investigation.

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