

# NEW DEVELOPMENTS IN LOW BETA SUPERCONDUCTING STRUCTURES

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*Two different materials, lead and niobium are currently applied to low beta superconducting cavities. New developments in the field are signaled while scanning the different technological approaches utilized throughout the whole scientific community. It will be seen that in spite of its thirty-year investigation, lead and lead-alloy technology applied to superconducting cavities is far from being fully mastered and there is still room for improvement. Both bulk niobium and niobium clad copper are technologies already transferred to industry which provides high reliability albeit at high costs. Niobium sputtering onto copper is appearing on the scenario of low beta resonators, passing from the stage of prototype study to the stage of cavity installation into a Linac.*

Key words: Superconducting cavities, Radiofrequency structures, Accelerator technology, Lead alloys, Niobium, Sputtering.

## 1 Introduction

Excellent reviews on low beta superconducting RF structures have been made in past years by J. Delayen [1-3], K. Shepard [4] and D. Storm [5,6]. The most recent [6] has already reported a complete panorama of the current research throughout the whole “low beta community”. Only a couple of years have passed since then. This is too short a time compared to the average time needed for technological innovations. Who deals with developments of large scale devices such as superconducting resonators, knows only too well that more than two years are needed from the birth of an interesting idea up to the installation of the “piece into the accelerator”. If in addition severe quality controls are needed, work-times are even longer. In real life any new development concerning low beta superconducting structures is rarely a breakthrough, but more often it is fruit of patient work made up of an enormous number of little steps.

Hence, in the author’s opinion a capillary review on “who’s who” and “who’s making what” in low beta cavities, will perhaps be useful for the next workshop, but

it is not what specialists need now.

What instead the author feels needed at present, is to use such an opportunity in order to: i) inform about new technical developments outside of traditional schemes; ii) signal some little details that even if not striking, can make us save efforts and time; iii) draw attention to what could be transposed into our field from beta 1 resonators technology; iv) put in relief where technological limitations are and what could be required for pushing the quality of results higher. Mainly the author hopes by such a review to stimulate further discussions, to give an opportunity to reflect about what normally is not considered and lastly - since criticism is a more constructive tool than approval - to induce those who do not agree with the following evaluations to comment on them.

We will try to attack the problem by looking at new developments in low beta structures throughout the three main existing construction technologies: the one of lead and lead alloys, the one of bulk niobium and niobium-clad copper and last the one of niobium sputter-coated copper.

## 2 THE TECHNOLOGY OF LEAD AND LEAD ALLOYS

Literature often reports that “for such RF applications where not high level performances are required, the possession of lead electroplating technology allows the achievement of fast results, with modest equipment and is relatively inexpensive”. That is particularly true of low frequency structures because of the already low BCS losses. Heavy ion Linacs have been built thanks to the lead plating technology (figure 1), e.g., in the case of the University of Washington beam has regularly been provided to users for years [5].

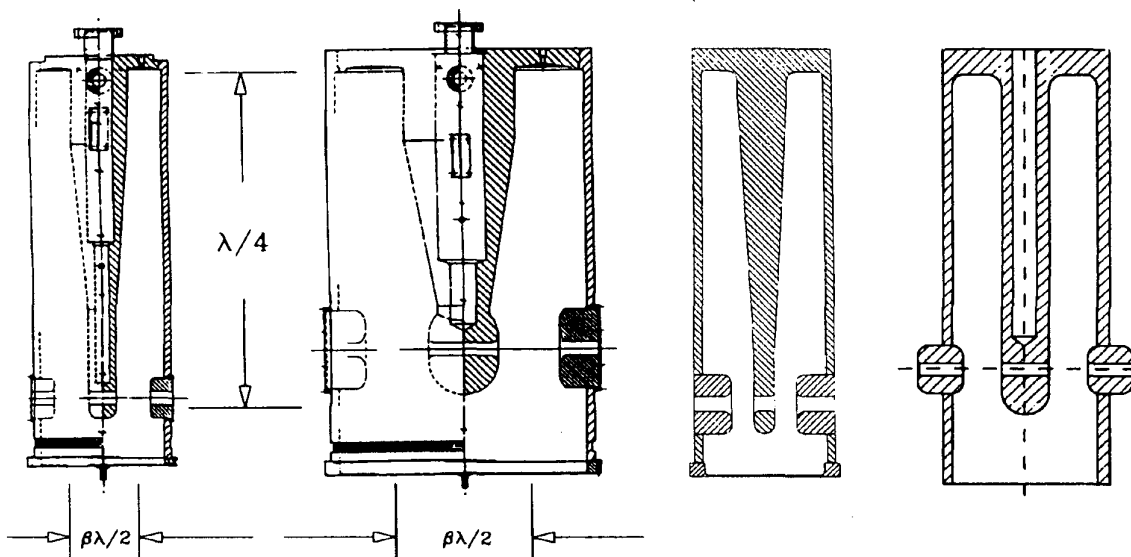


Fig. 1 Different types of QWRs utilized for lead plating [5-6]: from left to right the Seattle model, the Stony Brook model and Legnaro model.

However lead has an unstable surface and several precautions had to be taken to prevent surfaces oxidation. One of them, on the wave about ten years ago, consisted in plating a bigger lead thickness and partially removing it, leaving the first one-two microns plated. That was indicated as beneficial because of reduced residual losses, increased long term stability and field emission limit [1].

Looking for more direct plating procedures in order to prevent the contamination of the cavity interior during the post-plating treatment, superconducting alloys having more stable surfaces than pure lead were considered. So lead-tin was adopted as superconductor for re-entrant cavities of the Munich separated-orbit Cyclotron [7] displayed in figure 2 and for Quarter Wave Resonators (QWR) in the Stony Brook Linac [8]. Everybody working with lead-tin refers: "acetone rinsing gives a mirror-like finish, being stable even after long term exposure to air", or also "the lead-tin plating can be followed only by rinsing with large volumes of water".

Lead-tin technology has already provided brilliant results [8,9] both at Munich and at Stony Brook.

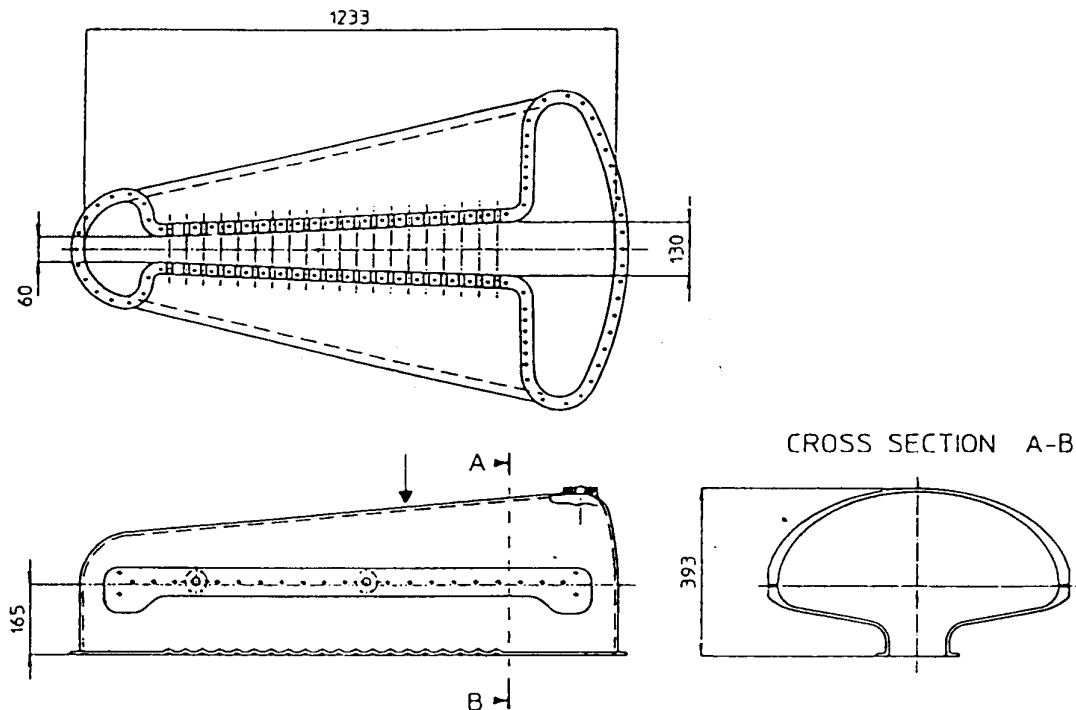


Fig. 2 Layout of the TRITON lead-tin copper cavities at Munich [7].

However there is something for which pure lead plating was preferable to lead-tin and it is represented by the difficulty to control the tin percentage during plating. Lead-tin films with 2% and 4% tin content were deposited on copper samples [10], and in both cases surface analysis displayed a tin content higher than the one established during preparation of the plating bath.

When observing the superconducting transition of these same films, it appeared that the lead-tin critical temperature value was only slightly higher than the one of pure lead films (less than one tenth degree). On the other hand the Residual Resistivity Ratio (RRR) value dropped from 50 (pure lead) to 24 for the 2% tin sample and to 20 for the 4% tin sample.

It can be shown that the BCS surface resistance decreases exponentially versus the reduced temperature  $T/T_C$ , being also proportional to the square root of low temperature normal state dc resistivity. That implies that even if  $T_C$  acts exponentially, an increment of a fraction of one tenth Kelvin is practically nothing compared to how much is lost due to the resistivity drop. More clearly, pure lead has lower BCS losses than lead-tin. Certainly lead-tin has a higher  $H_{C2}$  than lead, since its Ginzburg-Landau parameter  $K_{GL}$  is higher than for lead. But it is not clear if in radiofrequency high  $H_{C2}$  means better performances. On the other side the value of  $H_C$  for pure lead remains practically unchanged for not large amounts of tin.

Moreover if superheating occurs, the higher  $K_{GL}$  is, the lower the superheated critical field is. In addition the more tin is added to lead, the smaller the coherence length becomes. Hence a possible proximity effect of normal areas will extend onto a smaller and smaller length as the tin content is increased.

## 2.1 The problem of passivating a lead surface

The previous considerations would make us suppose that lead would not be a material worse (if not better) than lead-tin for superconducting radiofrequency, once the problem of lead surface instability is solved.

This problem however is of easy solution. It is possible to passivate lead surfaces in a simple way so that on exposing them to open air, no sign of oxidation appears for several days [10]. The recipe consists of an accurate rinsing of the fresh-plated surface with pure deionized water by means of consecutive dilutions. Then without delay, the resonator must go into a light acid solution (1% Acetic acid water solution at 90°C, or in alternative 5% phosphoric acid water solution at room temperature) and remain there for 8 seconds. Then it follows the same rinsing procedure with deionized water. The acid step does not etch lead since it only dissolves oxides and complexates the surface. The trick consists in carefully removing any trace of fluoborate by means of subsequent dilutions: if this is done, there is no need to soak in ammonia or in any chelating solution as suggested by previous literature. Black traces and shadows indeed are caused by residual fluoborates left on the surface due to imperfect rinsing. The piece can then be dried with nitrogen. Ethanol or acetone rinsing must be avoided, since they dehydrate the lead hydroxide into PbO (that has the typical yellowish colour).

Since electromagnetic fields in a cavity are confined within a few London depths, surface stability is a must, but it is not the only requirement for high performances.

The growth mechanism of a lead film on copper surface must still be fully understood. Nevertheless lead is the first superconductor used for accelerating cavities, however much has still to be done. In fact the main problem from which cavities suffer, is performance reproducibility. It must be made clear that when results are not reproducible not all process parameters are under control. Therefore the only remedy consists in mastering the whole process from substrate morphology, to the nucleation at the interface and from that to the coating microstructure.

## **2.2 The importance of plating parameters.**

More than once the author has gathered from different sources in different contexts that large thicknesses of lead film should be avoided because of the reduced thermal conductivity of thick coatings. Actually there is certain experimental evidence that large thicknesses are responsible for low Q-factors. However after a simple calculation of the lead film thermal conductivity, one immediately realizes that it cannot be responsible for low Q-factors. Moreover the higher the film thickness is, the higher the RRR becomes, since the grain size increases as its thickness increases..

A possible explanation to that, supported by electronic microscope sample investigation, is that any defect of the copper substrate such as dislocations, grain boundaries or surface roughness, will be reproduced and amplified by the lead film. In the same way a thin protrusion on the first layers of lead, will act as a nucleation center for a growing microparticle in poor contact with the film surface. And an electroplated surface is full of microparticles like this. They can be even superconducting at practically zero-field, but as soon as RF power is switched on, temperature rises. As a consequence the critical field decreases until the microparticles are completely normal.

Porosity acts in the same way. Porosity can be of two types either inclusion porosity or crystallographic porosity. Inclusion porosity may arise from small areas on the substrate surface on which, during the early stage of electrodeposition, metal deposition does not occur, although a bridge-over may arise at a later stage. Such small areas that work as porosity precursors, can be metallic inclusions, oxides or sulphides, mill scale or polishing abrasive residues, grease and dirt present on the substrate surface. Another kind of precursor are minute craters on the substrate. Of course defects of such a kind are the most common for electropolished substrates, being mainly due to the activated erosion that a bubble of oxygen promotes when sticking to the copper surface. Depositions do not occur on such precursors, either because they are poor electrical conductors or because their electrochemical properties differ so much from those of the clean substrate material.

Crystallographic porosity instead is caused by structural defects, caused either by the base metal or by electrolysis parameters. In this respect epitaxy governing the growth of a single grain and pseudomorphism may induce a lack of coherence

between parts of the growing deposit and the substrate.

Higher substrate temperatures and low deposition rates provide higher surface mobility of the deposited species and as a consequence large grains and more compact films. Increasing temperature of the plating electrolyte must be deeply investigated, because films grow in an aqueous solution and even low temperatures could oxidize them. Deposition rate is instead a parameter of known effect, the lower it is, the flatter and smoother the coating.

The substrate treatment in this context becomes of capital importance. According to this consideration, if a copper substrate is tumbled or electropolished or chemically polished, once coated, all parameters being constant, it should show different performances. As yet there is no systematic investigation on that. However something is proved: the smoother the copper surface, the better the cavity works. The author experience in this case is that the highest performances were obtained with cavities that were sequentially tumbled, electropolished, and chemically polished in a SUBU5 bath, the "wonder-polishing" found at CERN for LEP niobium sputtered copper cavities [11].

It could be interesting to resume an old idea [12] already suggested by Delayen [1] already in '84: copper plating copper before lead plating it. We have verified that copper plating is really a benefit against roughness: lead, after plating, has a considerably low roughness. However there is a not negligible probability of the appearance of microbubbles or poor adhesion points i.e. of further defects due to copper plating.

In this respect it must be reported that all baths currently adopted for lead plating make use of a moderator, that is generally a large molecule organic compound, that by its screening action on microscopic fields, favours a more ordered lattice growth. Animal glue or isinglass had been used over 20 years ago [13], saccharin, peptone or gelatine work too. Shinol (an aqueous mixture of orthoethylaniline, betanaphthole, fluoboric acid, Ethommen) provides the best results. Additives in the plating bath are responsible for making the whole process less controllable. First, because the ratios of the constituents are based only on empirical rules; second there is a strong limitation that is Shinol aging. Organic additives could be avoided when working in pulse plating regime. However no one at present has complete results of this particular application on superconducting resonators. Work on this subject is under development at Stony Brook for lead-tin by means of methylsulphonate baths [14] and at Legnaro for lead by means of the traditional fluoborate bath.

From this outlook it can be realized that under lead plating there is no black magic, as it was informally said some years ago. Non reproducibility of lead plated cavities only means that not all parameters are controlled.

It was in the author's hopes to persuade the reader that lead plating technology

is not on the way of extinction at all. But it could still be applied as a starting point for tricky geometry structures that require years of development if other solutions were adopted.

### 2.3 Normal conditioning or plasma processing?

Before concluding the paragraph, it is worthwhile to signal one study on processing plated resonators by Freon discharge. This work was presented by J. Noe' [15] already in 1993, but it could aid people that fight daily against multipactoring, to save a lot of time. "The process consists in leaking a Freon-11 ( $\text{CCl}_3\text{F}$ ) vapour through a QWR beam hole, while exciting one of the interior multipactor levels with CW radiofrequency. The gas leak is set for 1 mTorr ..... the applied RF power is typically 20 Watt of which half goes initially to the RF field, half is available to electrons. As the leak is opened the RF pick-up signal develops microsecond pulses and a blue-gray discharge is maintained for 1-5 minutes. The ripple structure quickly fills in; the multipactor increases in amplitude and disappears in other 1-5 minutes. After this no levels can be observed even with the sensitive test of slowly ramping up CW RF..... After processing the resonator is installed in the test cryostat and cooled without baking. Depending on the exposure to air during installation, some multipactoring can reappear, but this can be eliminated by pulsed RF conditioning at liquid nitrogen temperature. ...  $\text{CF}_4$  should also work". Noe' suggests to use this procedure also for treating copper or niobium. In this respect it should be mentioned that the technology of Reactive Ion Etching (RIE) is well developed and its application to the superconducting cavities as last treatment after chemistry, could reserve agreeable surprises. In the case of application to copper however, It must be mentioned that  $\text{CCl}_4$  is adopted instead than  $\text{CF}_4$ .

## 3 THE TECHNOLOGY OF BULK NIOBIUM AND NIOBIUM-CLAD COPPER

Bulk niobium and niobium-clad copper are treated by the author as kindred technologies. The reasons for such a choice are the analogies both in construction technique and in material characteristics and in results. Let us consider attentively three different examples of Quarter Wave Resonator: the Japanese niobium-clad copper QWRs for the JAERI tandem booster [16-18], the Legnaro double wall bulk niobium resonator for the low beta section of the ALPI Linac [19, 20] and the paired niobium Quarter Wave coaxial line for the New Delhi booster Linac [21] (fig. 3). Analogies in construction are: the use of Electron Beam Welding (EBW) and the type of surface chemical/electrochemical treatment potentially applicable to all of them. The central shaft of Japanese cavities is in bulk niobium. Analogies in material characteristics derive from the consideration that in both cases, either cooling is directly provided by liquid helium or it is provided by conduction throughout a copper

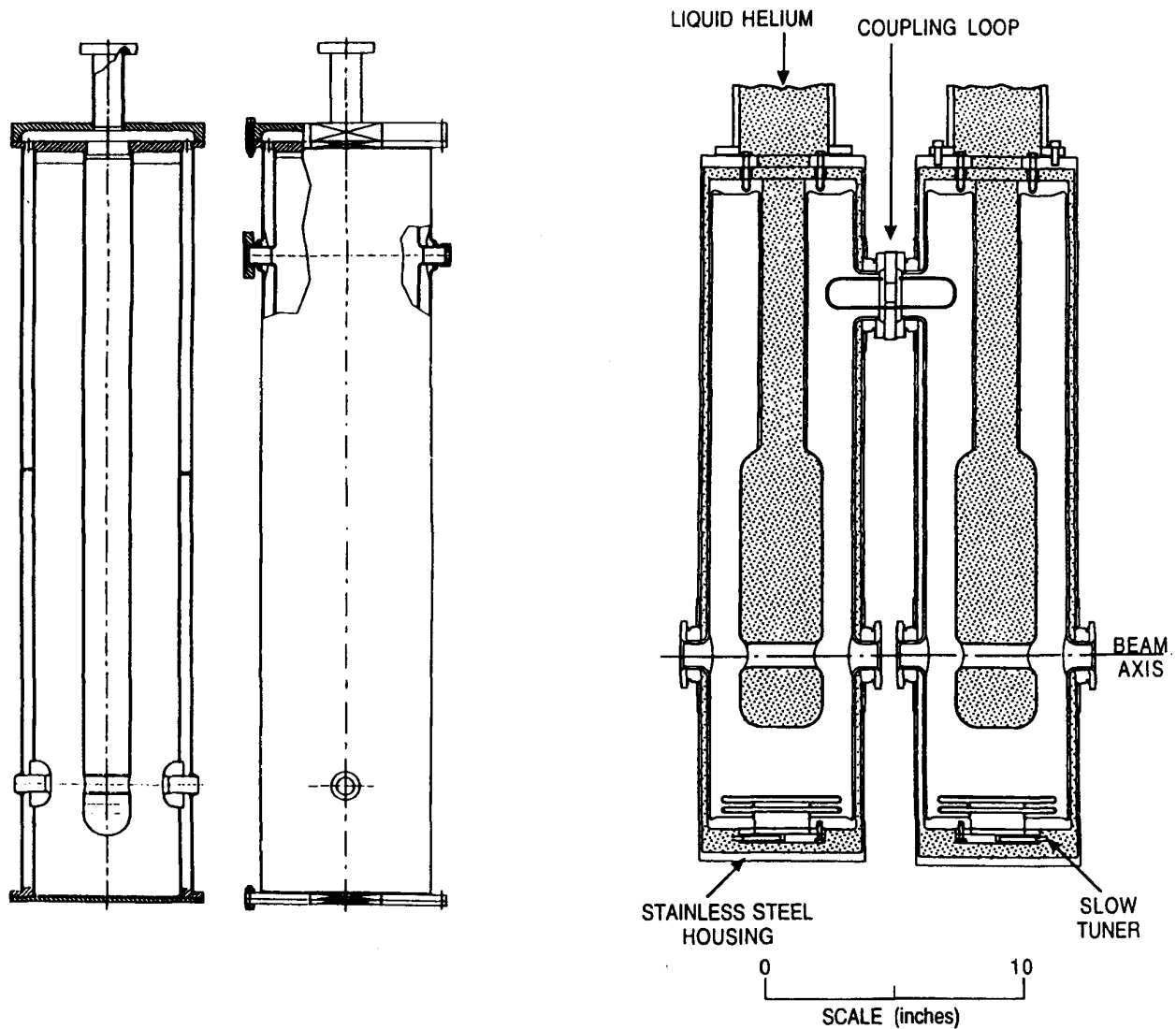


Fig. 3 The Legnaro (left) and New Delhi (right) double wall bulk niobium QWRs [19-20, 23].

bulk, a thickness of the order of a millimeter is sensed by electromagnetic fields as a bulk rather than as a film. Especially if compared to the few hundreds of Angstroms of penetration depth. Moreover unless the explosion during the bi-layer cladding does not affect the RRR starting value of niobium (and this is improbable), for both niobium and niobium-clad copper RRR is of a few hundreds, while for sputtered films RRR is of a few tens only. Analogies in results are the type of dependence of Q-factor versus accelerating field. After having got rid of field emission, bulk niobium cavities display a practically flat curve. A slight slope exists for niobium clad copper [18], but this is considerably smaller compared to sputtered niobium resonators that instead



suffer from a marked Q-degradation versus field. It is worthwhile to mention however that the RRR of niobium used for Nb-clad Cu resonators was 80 for most resonators, 150 in the best case [18]. Legnaro bulk Nb cavities, in analogy to beta 1 cavities, at least for the cavity regions exposed to fields, utilizes material with RRR around 200-250. Could it be put in relation with the experimental evidence for sputtered cavities that the higher RRR is the smaller the slope?

### 3.1 Quarter Wave Resonators.

Getting more into detail about the three a.m. examples, we can add that firing of the resonator cannot be performed for JAERI and New Delhi resonators, being temperature limited by the presence of copper and stainless steel respectively. For those Legnaro resonators made entirely of niobium, titanification can be done by inserting the getter into the double wall. About Legnaro Nb bulk cavities it can be said that RF performances of such structures are reliable, while the only limitation observed up to now has been their sensitivity to mechanical and pressure disturbances. However it has been seen that the amplitude and phase of the overcoupled cavity remain locked by a standard control system for an increasing He bath pressure from 1 to 1.4 mbar. It is also useful to cite that a "jump in performances" making  $Q$  move to the scale  $10^9$ , was gained by means of the 100 bar water rinsing just before the RF test. This procedure, imported by the beta 1 cavities world, that in its turn took it from the semiconductor industry, could allow improvements for all types of cavities where applicable. For niobium sputtered QWRs indeed high pressure rinsing is currently applied to the copper substrate before sputtering.

The problem of the high cost of this double wall resonator due to the large number of EB-welds could become a minor problem when dealing with large numbers of cavities. Moreover many weld joints could be saved, in the author's opinion, being favoured by the high formability of pure niobium. Instead of rolling and longitudinal welding of niobium sheets, seamless tubes can be made by flow turning or backward extrusion. But again dies and tooling costs are amortized only by large numbers.

It may seem obvious that "the fewer welds there are, the better it is", but often obvious things are not discussed, maybe just because they are obvious. Apart from parasitic defects such as projections, microbubbles or craters, welds inherently possess compositional and microstructural heterogeneities due to a transition from wrought metal to solidified weld metal, through Heat Affected Zones (HAZ). Electron Beam welding, even if it can produce in a single pass deep, narrow, and almost parallel-sided welds with low total heat input and relatively narrow HAZ, at the moment is the main source of defect production in resonators. In confirmation of this, measurements have been done proving that the RRR of a weld depends significantly on the residual pressure in the welding chamber [21]. And for manufacture cost reduction, EB-welds are often made under high vacuum and not under Ultra-high

vacuum. Recently DESY has been developing a technique that “practically eliminates the weld”. The tube after having been welded is electromagnetic hammered in order to get a fine grain size, then it is annealed or even fired in order to re-establish the high thermal conductivity [22].

The niobium coaxial line for the Indian booster is under development [23]. The structure consists of a pair of QWRs strongly coupled with a superconducting loop. Coupling splits the accelerating eigen-mode into two resonant modes each of them covering a portion of the full velocity acceptance range of the original single cavity mode. Paying the price of a reduced range of useful velocity acceptance for each element, it is possible to reduce the number of independently controlled elements. This cavity must be cited also for the niobium bellow used for frequency tuning. In itself this feature is a technical detail, but if properly adapted for other types of QWRs, could mean a not negligible improvement for the whole QWR community. In fact niobium sputtered copper cavities for the high beta part of Legnaro Linac [24], having external beamports cannot be fine tuned by setting the position of beamports, since they are external to the resonator. The bottom plate tuning gives an adjustment of not much more than 20 KHz. Hence the right frequency is found by adjusting the central shaft length. Since only one tenth of a millimeter cut from the shaft means a change in resonant frequency of about 300 KHz, the resonator must go backwards and forwards from the mechanical workshop to the RF bench. A copper bellow sputter-coated with niobium would allow looser mechanical tolerances.

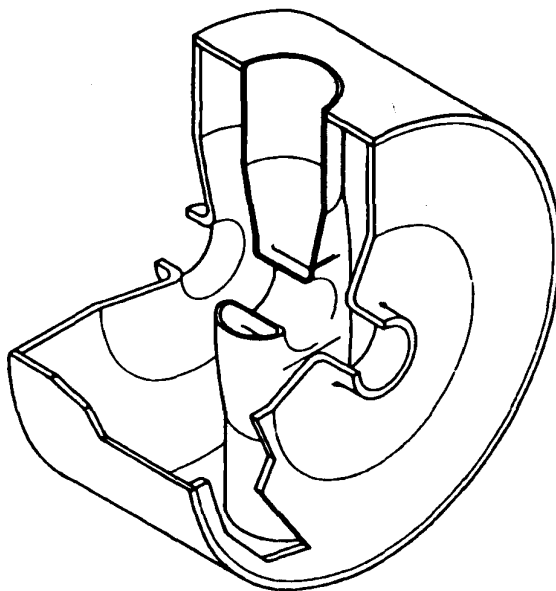


Fig. 4 The 805 MHz bulk niobium two gap spoke resonators [25-26].

Something more about the New Delhi resonator: the niobium is closely jacketed in a vessel of stainless steel which contains the liquid helium. The fact that the cavity is hermetically closed makes any further cleaning of the resonator interior impossible. However a clean room assembly, should make unneeded re-opening the resonator. Also hermetically closed are Delayen's 850 MHz 2-gap spoke resonators [25-26] in figure 4 that must be cited at least for their modularity, since several units can be stacked together to make a multigap cavity.

### 3.2 Niobium clad copper resonators

It is interesting to take a look to niobium clad copper structures (fig. 5).

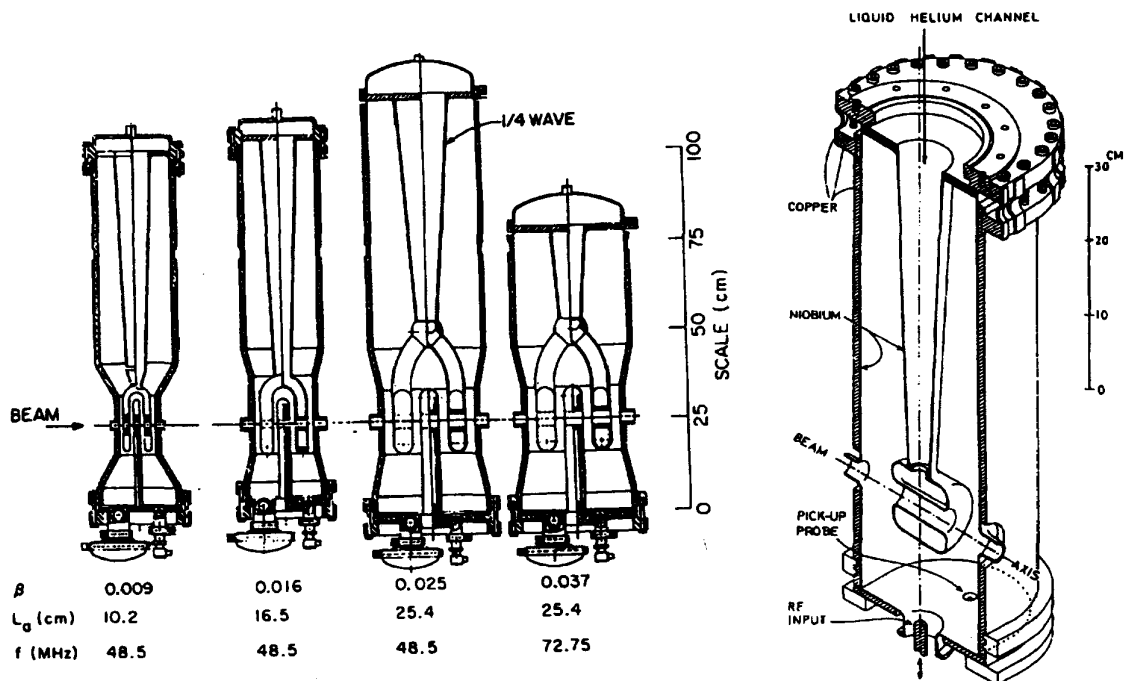


Fig. 5 Niobium clad copper structures: the Argonne interdigital resonators (left) [28,29] and the JAERI QWR (right) [16,18].

In truth all these cavities, both the Argonne National Laboratory Split Loops [27] and the interdigital QWRs [28,29], 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.

### 3.3 Stress in niobium: is it a problem about which we should worry?

Taking hint from such cavities this review can insert another interrogative in the puzzle of the unsolved questions regarding the hydrogen role in Q-disease. A good review on the subject on this subject was made by Bonin a few years ago [30]. Together with this it is advisable to read in particular one work of Isagawa [31] and one more recent from Halbritter, Kneisel and Saito [32].

JAERI resonators suffer from Q-disease and this was reported [18] already in '91. On the other hand JAERI cavities are electropolished (up to 30 microns are removed) and it is also well-known that niobium surface can be hydrogen charged during electropolishing. Of course being the resonators buffered with copper high temperature annealing of niobium is not possible.

Beside these considerations, it is worthwhile to add one more very well-known element in material science, but not familiar to everybody in the accelerating cavities community: superdiffusivity of Hydrogen in niobium. The anomalous enhancement of the diffusion rate of hydrogen in V<sub>a</sub>-metals (V, Nb, Ta) induced by the application of tensile stress parallel to <111> direction has been studied since '83. As shown in figure 6, the superdiffusion rate of hydrogen in niobium is between 100 and 1000 times larger than the normal one under zero stress [33].

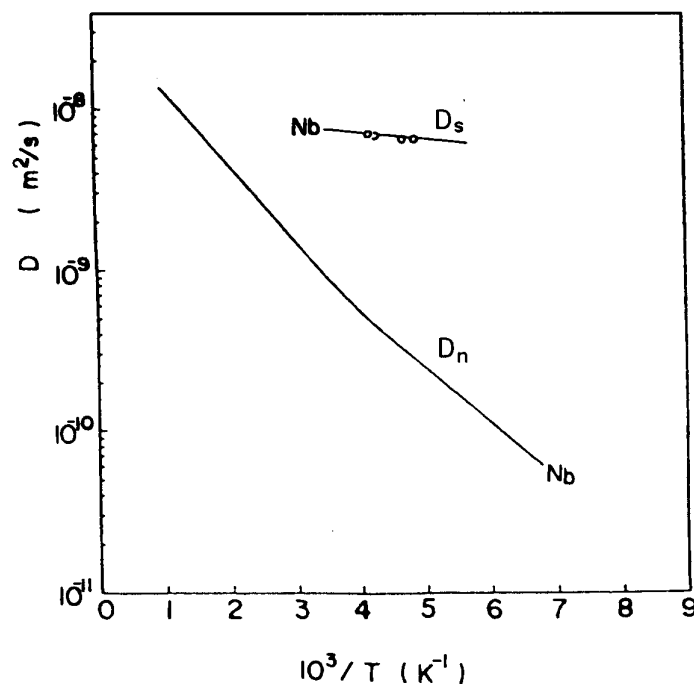


Fig. 6 The superdiffusion coefficient  $D_s$  and the normal diffusion coefficient  $D_n$  for hydrogen in niobium plotted against temperature (after ref. 33).

The phenomenon is ascribed to the characteristic of the motion of hydrogen through tetrahedral sites which are stable sites introduced by the application of external stress.

We know that other types of QWRs such as niobium sputter-coated cavities and double wall bulk niobium cavities do not suffer from Q-disease. The cladding procedure of copper with niobium, certainly leaves stress in the material. This stress cannot be released because no annealing can be done. Of course a spontaneous question arises: is Q-disease in niobium clad copper in any correlation with superdiffusivity of hydrogen in niobium?

Someone could ask if material induced stress also affect the material thermal conductivity, and consequently limit the maximum accelerating field. The answer is negative. Stress can decrease the thermal conductivity only below 4.2 K, as it can be seen in the figure 7, that reports a well-known result for niobium [34]. The presence of the minimum can be explained by writing the thermal conductivity  $K$  as the sum of several terms dependent on temperature.

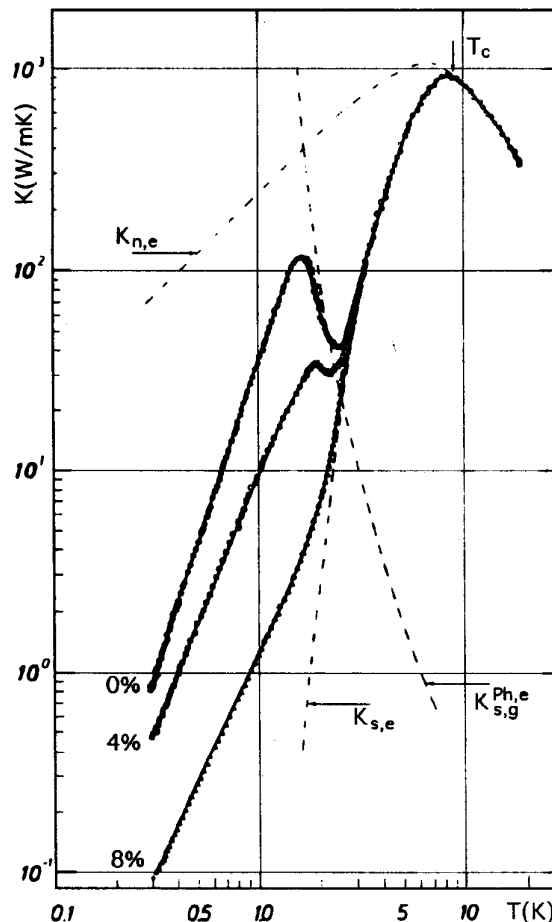


Fig. 7 Temperature dependence of niobium thermal conductivity sample that was plastically deformed of 0 %, 4 % and 8 % respectively (after ref. 34).

In the case of undeformed niobium the curve exhibits a minimum around 3 K and a minimum at 1.8 K. Below 1.2 K data are consistent with a  $T^3$  relationship due to the normal boundary scattering of lattice waves. Above the critical temperature the thermal conductivity increases with increasing temperature, passes through a maximum and then decreases with increasing temperature. In this temperature region the electronic thermal resistivity  $R_{n,e}$  obeys to the law  $R_{n,e} = aT^2 + b/T$ , where the first term describes the scattering of conduction electrons by phonons and the second the scattering by impurities.

In the superconducting state the thermal conductivity  $K_s$  of the undeformed niobium is given by  $K_s = K_g + K_{s,e}$  being  $K_g$  the lattice thermal conductivity and  $K_{s,e}$  the contribution of quasiparticle excitations.

The thermal resistivity  $K_g^{-1} = R_g = R_g^{ph} + R_{s,g}^{ph,e}$ , where  $R_g^{ph}$  is the lattice thermal resistivity due to boundary scattering of the lattice waves,  $R_{s,g}^{ph,e}$  is the lattice thermal resistivity due to the scattering of phonons by the remaining normally conducting electrons.

Since the density of quasiparticle excitations decrease against temperature, the quasiparticle conductivity  $K_{s,e}$  decreases with temperature and the lattice-quasiparticle interaction resistivity  $R_{s,g}^{ph,e}$  decreases too. This explains the minimum and the peak displayed in figure.

Plastic deformations inhibit thermal conduction since they add a contribution  $R^{r\sim}$  to lattice thermal resistivity. Such a contribution can again be distinguished in two terms: one due to boundary scattering of lattice waves and one another due to quasiparticle excitation scattering.

#### 4. The technology of niobium sputter-coated copper.

Since the CERN pioneering work of the early eighties [35-37] up to the success of technology transfer to industry of nowadays for LEP electron cavities [38], niobium sputtering technology has conquered a solid position in the framework of resonator construction technologies. The improved thermal conductivity of a few microns of niobium sputtered onto one centimeter thick oxygen-free copper substrate, the high mechanical stability and the significant reduction of material costs make the sputtering solution an attractive alternative to bulk niobium use. Research programs on sputtered Nb/Cu QWRs are carried on independently at the Australian National University in Canberra [39] and at Legnaro National Laboratories [40]. The former has developed a DC magnetron sputtering configuration; the latter a biased DC diode sputtering configuration (figure 8). For both groups the main activity for several

years has been a long and systematic research starting from the design of cathodic configuration and the search for a uniform film thickness, up to the study of deposition parameters effect on superconducting proprieties.

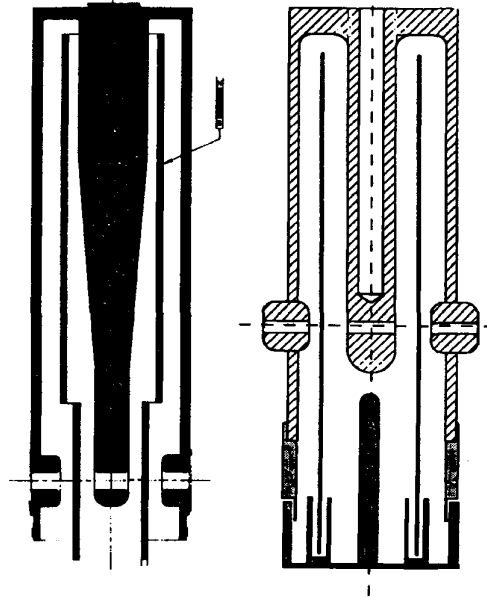


Fig. 8 Sketches of the ANU magnetron configuration [39] and LNL Diode biased configuration [40] for sputter-coating QWRs.

Niobium critical transition temperature to the superconducting state indeed drops drastically versus oxygen contamination decreasing by 1 K each O<sub>2</sub> %, and BCS losses depend exponentially on critical temperature. In such a context Canberra is devoting strong effort to the comprehension of the mechanism of surface degassing accompanying the discharge sputtering of niobium films. In Malev and Weisser's hypotheses, the source of contamination is the decomposition of the surface oxides on copper substrate and niobium cathode exposed to plasma discharge. Hence they investigate at the moment the possibility of degassing the sputtering system by a preliminary discharge in helium atmosphere [41].

Regarding Legnaro niobium sputtered 160 MHz copper QWRs having Q values of the order of 10<sup>9</sup> and accelerating fields around 7MV/m at 7 Watt of RF power are produced. The sputtering procedure is described elsewhere [42]. We will only cite the main parameters characterizing the sputtering process. The copper substrate is subsequently tumbled, electropolished and then chemically polished, the vacuum level before discharge ignition is in the low 10<sup>-9</sup> mbar range, the coating thickness is around 5 microns, and the resonator temperature during deposition is around 600°C. Moreover the resonator does not have a flat shorting plate, but a half circular section curvature joints the inner and outer conductors. The capacitive coupler and

pick-up antennas are located on the bottom plate. That allows to simplify the coating procedure of the resonator

In the summer of '95, a cryostat equipped with four niobium sputtered QWRs was installed on the ALPI beam line just at the end of the middle beta section [43]. While for prototype production was quite a normal operation to produce resonators of 7 MV/m at 7 Watt, in the moment of real cavity production, the average field achieved was not more than 5 MV/m at 7 Watt.

## 5. NEW STRUCTURES

The Radio-Frequency Quadrupole (RFQ) accelerator structure, based on the concept of a strong and spatially homogeneous focus of ion beams [44] is attractive for the production of high current high brightness beams and is going to be applied in many low energy ion accelerators and for a variety of applications.

Development of Superconducting RFQs is taking place at Stony Brook [8], Argonne National Laboratories [45-47], Los Alamos National Laboratory [48] and Legnaro National Laboratories [49]. Figure 9 shows conceptual designs of a low frequency and of a high frequency superconducting RFQ and the prototype structure of Stony Brook, while figure 10 displays a MAFIA drawing of the structure put in production at Legnaro.

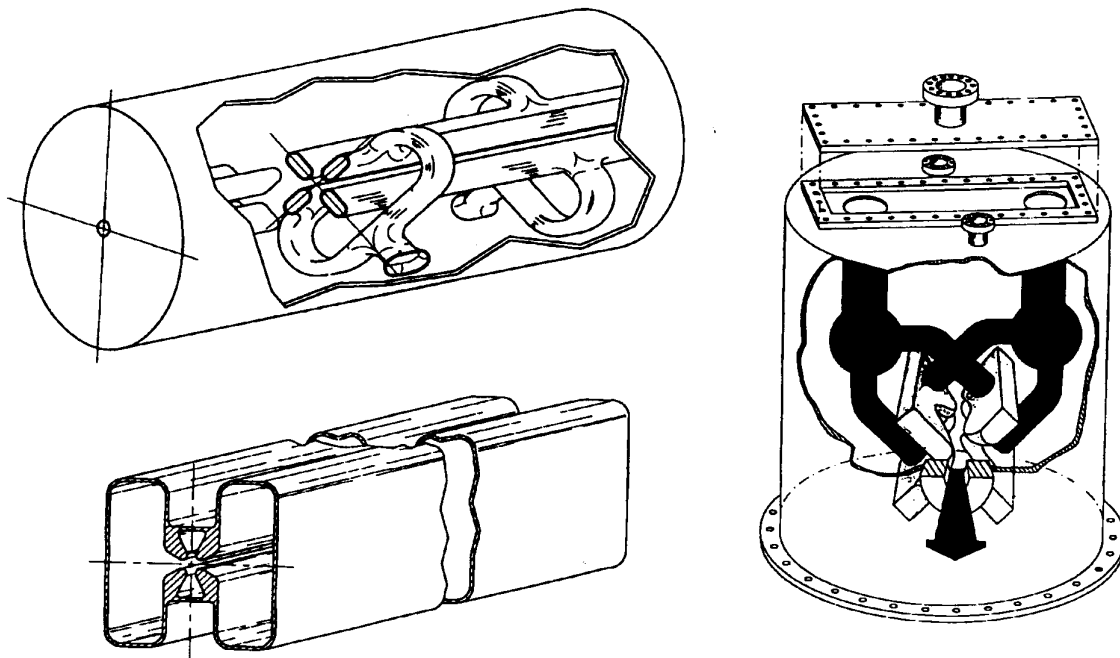


Fig. 9 Conceptual design of a low frequency RFQ (left high) and of a high frequency superconducting RFQ (left low) [after ref. 46]; sketch of the Stony Brook prototype structure for lead-tin plating [8].



The field is in continuous evolution. At this moment the RFQ community is still in the stage of a search for a continuous and progressive refinement. Hence it is not rare still to encounter changes in prototype geometries. The construction technologies also sweep from electroplated lead-tin to bulk niobium, to sputtered niobium.

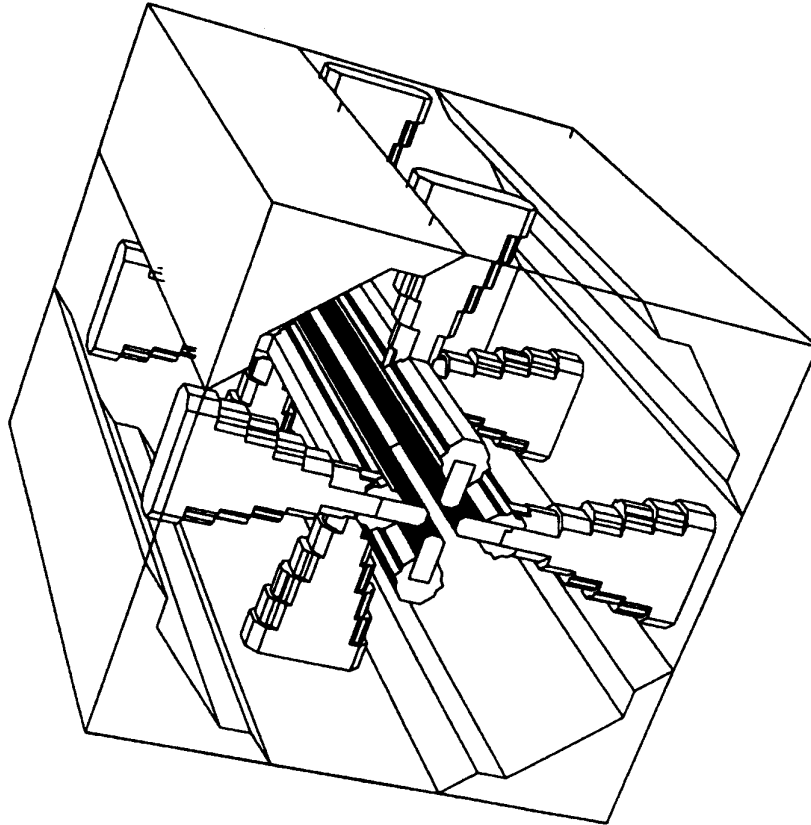


Fig. 10 MAFIA drawing of the structure put in production at LNL[49].

## 6 NEW MATERIALS

When the words “new cavity materials” appear, one is automatically led to think about B1 compounds such as NbN and NbTiN or about A15 compounds such as Nb<sub>3</sub>Sn and V<sub>3</sub>Si. However these materials do not find strong application for low beta structures since low frequencies mean also low BCS losses. The  $R_{BCS}$  losses of niobium at 4.2 K and 160 MHz are around 5 n $\Omega$  that is already a low value, especially because the real limit is the residual resistance.

The plot of figure 11 displays the lines of equal  $R_{BCS}$  in the bidimensional space of Critical temperature  $T_C$  and low temperature resistivity in normal state  $\rho_n$ . The calculations [50] were done computing Mattis and Bardeen integrals in the dirty limit

approximation, at the temperature of 4.2 K, frequency of 500 MHz and a strong coupling factor of 4. That means for instance that a NbTiN of 16.3 K critical temperature and 35 nΩ has a BCS resistance around 2 nΩ at 500 MHz. Since BCS losses scale approximately as  $\omega^{1.8}$ , it is enough to divide this value for a factor 10, for getting  $R_{BCS}$  values at 160 MHz. Of course a  $R_{BCS} = 0.2$  nΩ is smaller than the corresponding niobium value, but it will be completely dominated by the residual resistance that will certainly be much higher since it is an increasing function of  $\rho_n$ .

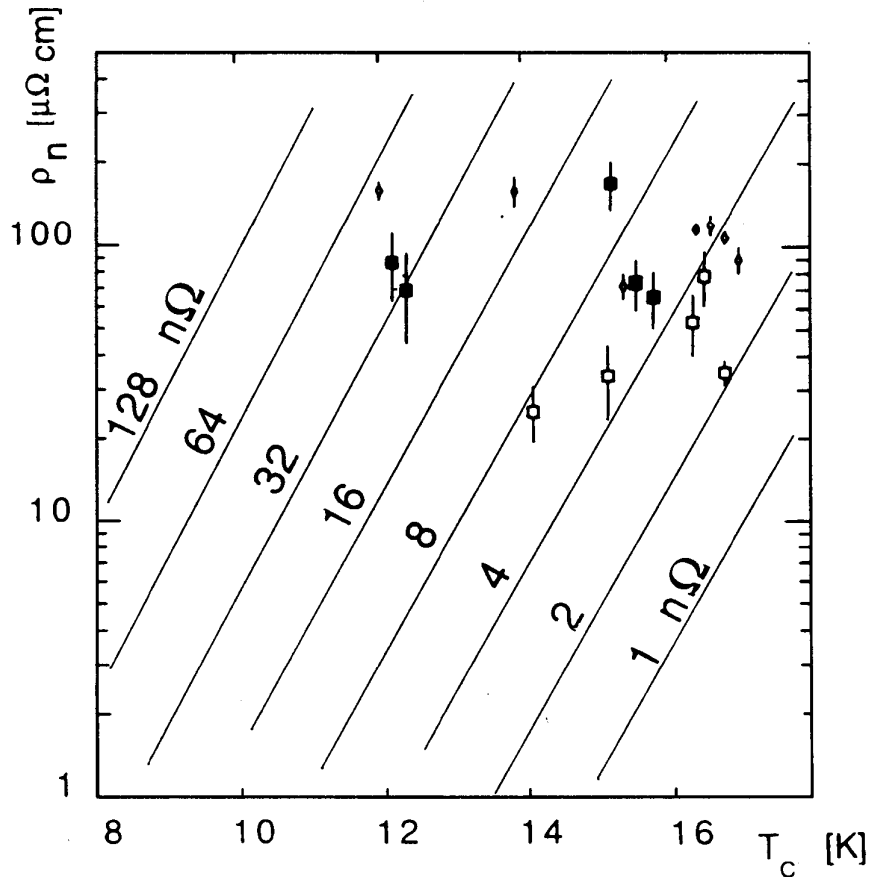


Fig. 11 Lines of equal  $R_{BCS}$  in the dimensional space  $(\rho_n, T_c)$  at  $T = 4.2$  and  $\nu = 500$  MHz. For comparison niobium has a  $R_{BCS}$  of 55 nΩ. The experimental data are relative to sputtered films of (NbTi)N at 200°C (full square); (NbTi)N at 600°C (empty square), NbN at 200°C (diamond), (after ref. 50).

For low beta structures, it would make much more sense to think of new materials in terms of substrate for niobium sputtering. Pure aluminum at a commercial purity of 99.999 indeed has a thermal conductivity at 4 K over 1000 W/m K, more than twice that of OFHC copper available for cavities. The problems of aluminum softness could easily be solved by increasing the wall thickness of the resonator [50].

One inconvenience instead could be represented by the the higher thermal expansion coefficient respect to that of copper that is already higher with respect to the niobium one.

All investigation on new materials however should be a logical consequence of a complete mastering of old materials. And it is in the author's opinion that this condition still has not been fully satisfied. copper production instead, escapes from the control of researchers. Not once only, OFHC copper billets were found having in their interior millimeter-size porosities. If these macroporosities can be revealed during machining of a QWR, they will never be detected once the billet is laminated for forming copper sheets, because of their sporadic density. If a troubleshoot will occur, it would be easy to attribute its cause to the enormous getter capability of niobium or to the poor respect of the hi-tech cleanliness obligatory for the whole manufacturing process of the resonator. But in truth nobody can guarantee that laminated air bubbles is not a problem.

Moreover another question to the scientific community: Who is really sure that niobium is the same on the two faces? The author has experienced different grain sizes on the two faces of some 3 mm thick 250 RRR niobium sheet samples. If this was not a random circumstance, would it mean that there is a preferred side of niobium sheets for cavity fabrication?

Of course an answer to this interrogative passes only through a continuous evolution of diagnostic tools. More than ten years ago, the only discrimination tool for evaluating the niobium film quality was the  $T_C$  measurement. As soon as purer films were sputtered it was realized that such a measurement was no longer satisfactory, since  $T_C$  was always more than 9.25 K. Then RRR was individuated as the key parameter. However RRR measures a percolative path in the superconductor and not the sample in its entirety. The inductively measured RRR is already a step forward. Now that RRR values over 30 are achievable, we find ourselves again in the situation of searching for a finer scale parameter.

Could such a parameter be the lower critical field  $H_{C1}$ ? Only further research can answer that. All of us working on this subject, are goaded to understand which still unknown perverse mechanisms make experimentally reached values always lower than theoretical expectations, and likewise what the antidotes against those mechanisms are.

## 7 CONCLUSIONS

Two different materials, lead and niobium are currently applied to low beta superconducting cavities. New developments in the field were signaled while scanning the different technological approaches utilized throughout the whole scientific community. Lead has poorer superconducting performances compared to niobium. But, though electroplating technology could look obsolete to some, it offers the not

negligible advantage that requires modest equipment and is of easier and faster application than niobium, especially when dealing with difficult shape surfaces. It was seen that in spite of its thirty-year investigation, lead and lead-alloy technology applied to superconducting cavities is far from being fully mastered and there is still room for improvement. On the other hand if a breakthrough will ever occur, it would be improbable that it comes from lead and not from niobium. Both bulk niobium and niobium clad copper are technologies already transferred to industry which provides high reliability albeit at high costs. Niobium sputtering onto copper is appearing on the scenario of low beta resonators, passing from the stage of prototype study to the stage of cavity installation into a Linac. Some more time will still be needed for making this technology well-established. As a paradox, even if niobium requires a more sophisticated technology than lead, sputtering variables are easier to keep under control than electroplating variables.

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