MODERN TECHNOLOGIES IN RF SUPERCONDUCTIVITY

H. Lengeler
CERN, Geneva, Switzerland

Abstract
The development and application of superconducting rf cavities in particle accelerators is a fine example of advanced technology and of close cooperation with industry. This contribution examines the theoretical and present–day practical limitations of sc cavities and describes some advanced technologies needed for their large scale applications.

INTRODUCTION

Since more than 20 years superconducting (sc) rf-cavities have been used with increasing success in particle accelerators [1-5].

In 1972, the first electron-beam was accelerated in the sc recirculating linear accelerator at HEPL, Stanford University [6]. In 1977, routine operation of the CERN/Karlsruhe sc particle separator started at CERN [7]. The first regular operation of a heavy ion booster took place at Argonne [8] in 1978 followed subsequently by a few others and a considerable operational experience of more than 100 000 hours has been accumulated since then in heavy ion linacs [9].

In 1988, 16 sc cavities started routine operation in the TRISTAN $e^{\pm}$ storage ring at KEK [10], followed later on by sc cavities in LEP, CERN [11] and HERA, DESY[12]. Most of the sc cavities were already produced by industry. In the United States at CEBAF, Newport News, a 4 GeV, sc recirculating linac for electrons with a 100% duty cycle is under construction [13,14].

At present, the use of sc cavities is considered for high intensity $e^{\pm}$ colliders (i.e. τ–charm and beauty factories), for linear colliders in the energy range well above 100 GeV and for the planned large p-p colliders LHC and SSC.

Projects of this kind do not only need an adequate production technology with a very high degree of reliability but also economic fabrication methods, surface treatments and assemblies. These arguments apply even more to sc cavities for large linear colliders [15] which are today under active discussion and for which another considerable increase in cavity performance will be essential.

Although a substantial increase of field levels and quality factors in sc cavities has been achieved we are still far away from the performance limits set by theory, especially in multicell cavities. Today it is commonly agreed that further progress will be mainly linked to developments in technologies of sc metallurgy, cavity fabrication and surface treatments. We do not expect that a single factor will increase performances dramatically and progress will be presumably bound to a whole bundle of improvements.

Up to now by far the largest effort has been applied for two superconductors: Pb and Nb. In future we cannot ignore the potential of superconductors such as A 15-alloys or the very recently developed high T_c oxide-based superconductors whose application to sc cavities will requlre even more complex material and surface treatment technologies.

The application of rf superconductivity makes use of a number of advanced technologies. High purity superconducting materials with very homogeneous and clean surfaces are necessary for the fabrication of cavities. Similar requirements are needed for thin sc layers deposited on a non–superconducting material such as copper. High quality shaping and welding procedures are essential. Clean and dustfree surface treatments of large multicell cavities with complicated geometry had to be developed. RF measurements and operation of sc cavities, whose quality factors may range up to 10^{10}, require sophisticated methods and equipments. Auxiliary items like rf-couplers and frequency tuners have to fulfil very demanding rf, mechanical and cryogenic requirements which are difficult to combine. RF superconductivity has also triggered the development of large refrigerators and cryostats operated at temperatures well below 4.2 K and with superfluid He.

In the following a few characteristic technical developments will be described. Methods will be mainly illustrated by examples of electron acceleration cavities fabricated from niobium (Fig. 1). Besides established methods possible improvements will be mentioned and discussed.

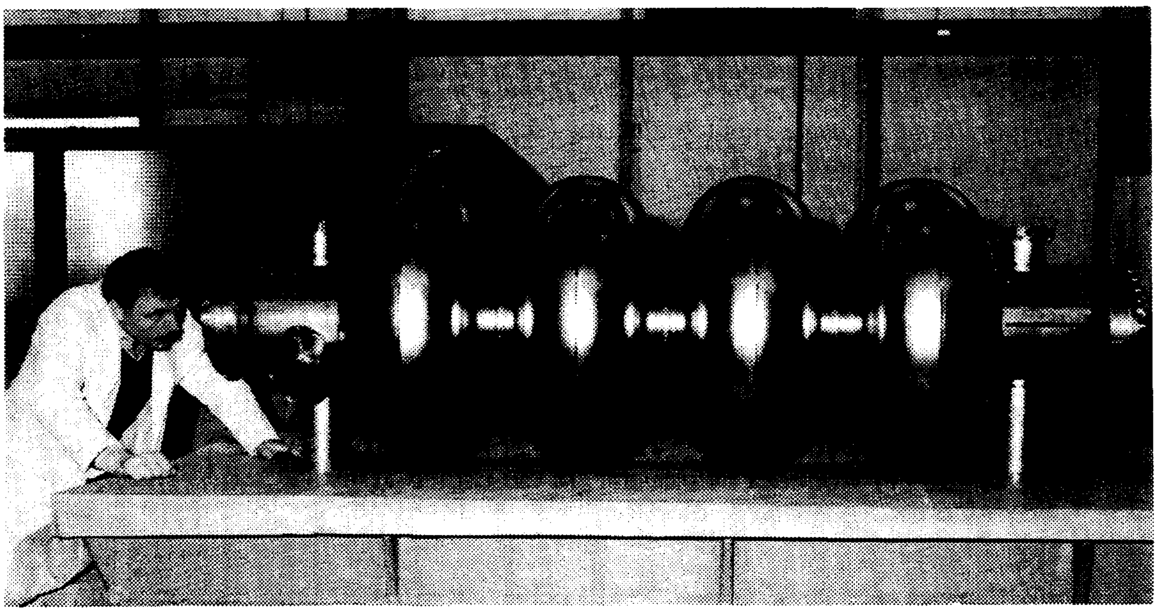

Fig. 1 A 350 MHz, 4-cell Nb cavity for LEP. The rounded half-cells are welded at the equators and at the irises. The cavity is equipped with coupling ports located at the beam tubes. Conflat stainless steel (316 LN) flanges are brazed to all openings.

1. LIMITATIONS OF SC CAVITY PERFORMANCES

At high frequencies and for temperatures below the critical temperature T_c the rf resistance of a superconductor decreases exponentially with temperature and its value can be made typically 10^5 to 10^6 times smaller than for copper at room temperature. The corresponding decrease of rf losses in sc cavities has attracted accelerator constructors because much higher acceleration efficiencies and higher CW accelerating fields than in Cu cavities can be reached [16-18].

Due to the Meissner effect the penetration depth of rf fields in a superconductor is much smaller than the normal skin depth and is in the region of 50-200 nm. RF superconductivity is therefore a surface effect. One may characterise rf losses of a superconductor by the surface resistance R_S (in Ohm). For cavities, losses are generally expressed by the so-called quality factor Q. For a given cavity geometry and rf mode, quality factor and surface resistance are related by the relation

$$Q = G/R_S$$

where G is a constant. For typical electron accelerating cavities, one calculates G = 280 Ohm. It is possible to reach reliably in large multicell cavities Q-values well above 10^9 which may be compared with typical Q values for Cu accelerating cavities of a few 10^4.

The measured surface resistances R_s can be described by the expression:

$$R_s = R_{BCS} + R_{res}$$

The result of the BCS theory can be approximated by the following expression for R_{BCS} (and for $T < T_c/2$)

$$R_{BCS} \sim (f^2/T)\exp\{-\alpha T_c/T\}$$

T_c: critical temperature; T: temperature: f: frequency, α: material constant; for niobium $\alpha = 1.85$.

It is obviously advantageous to use superconductors with high T_c. This is the reason why among the pure metals Pb and Nb have been chosen as most promising candidates and why one considers presently the use of high T_c alloys with great interest.

The experimental decrease of R_s is always limited to some finite value by the influence of a nearly temperature independent residual resistance R_{res}. Considerable experimental and theoretical work has been devoted to R_{res} which depends in a complicated and varying way on frequency, surface and material parameters. At present it is possible to reach reliably residual resistances in the range of a few 10^{-8} Ohm even in large multicell cavities. These values correspond to a decrease of surface resistance with respect to Cu of 10^6 and are low enough to satisfy the requirements of most applications where accelerating fields below ~ 10 MV/m are sufficient.

1.2 Field limitations [16,18]

In rf cavities for electron acceleration the major part of the inner surface is exposed to high magnetic or electric rf fields. In normal-temperature cavities rf fields are limited either by the warming-up of walls due to the large rf losses or by electron field emission and electron resonance phenomena (multipactor). For sc cavities one has to add the critical magnetic rf field H_c as another limit. For ideal Nb surfaces one would expect to reach corresponding acceleration fields of the order of 50 MV/m. However, for real surfaces, fields are limited to much lower levels, because there exist well-localised microscopic defects with increased rf losses. These defects, which are not related to the sc properties of the cavity walls, heat up their surroundings and eventually drive it to temperatures above its critical temperature T_c thereby inducing a thermally unstable process which finally leads to a fast field breakdown. Surface defects are mostly of trivial nature such as cracks and holes in weldings, welding beads, tooling marks, dust particles or residues from chemical treatments or rinsings. Other defects are imbedded, during production or lamination processes, in the surface regions or can be segregated at surface grain boundaries during intermediate or final annealings. For presently required field levels, the size of typical defects has to remain well below a few tenths of mm.

Another cause of field limitations are point-like electron sources - similar to the dc field emission sources observed at large area high voltage electrodes - and located at regions exposed to high electric surface rf fields. The emitted electrons are accelerated in large cavities to energies in the 100 keV or MeV range and hit cavity surfaces causing heating and emitting bremsstrahlung X-rays. Field emission loading is produced not only by the acceleration of electrons but also by the increased rf losses at regions warmed up by electron impact.

Investigations of electron sources on typical Nb surfaces for sc cavities have revealed that emitting sites may be produced either by dust particles or by segregations of foreign materials at the surface. The size of emitting sites may range down below the μm range.

2. Nb MATERIAL [19]

At present the favourite material for cavity fabrication is pure Nb. It has mechanical properties which allow easy shaping and welding of cavities with complicated geometrical layouts. For a long time a considerable effort has been devoted to the understanding of surface defects in Nb limiting the accelerating fields. Careful surface treatments and improved inspection methods made it possible to avoid larger defects or to eliminate them after their localisation. In this way, fields could be gradually increased but one could anticipate that at much higher field levels the size of defects to be detected and to be eliminated would become very small and their number prohibitively large. It was pointed out by H. Padamsee [20] that the threshold field for thermal instabilities could be increased if the thermal conductivity λ of the cavity wall was improved. Model calculation for defect stabilisation have shown that breakdown fields scale approximately with $\sqrt{\lambda}$ for a given type of defect. This behaviour has been confirmed by many cavity tests at different frequencies. Fortunately the heat conductivity of the Nb initially used for cavity fabrication lends itself to substantial improvements, essentially by reducing the interstitially dissolved elements O, N, C and H. Industry has taken up successfully this challenge and was able to raise residual resistance ratio (RRR) values for Nb material from a typical 40 (corresponding to a heat conductivity λ = 10 W/m x K at 4.2 K) to values well above 300. These advances were made possible by more and slower melting cycles of Nb in ingots, by better monitoring and control of furnace vacuum, and also by additional precautions during rolling and annealing of Nb-sheet material. The RRR of industrial products could even be raised to values of up to ~ 700 by solid state gettering with yttrium and titanium foils [21]. The procedure uses a metal with higher affinity to O, N or C than Nb which is brought in contact with Nb during a high temperature treatment in a vacuum furnace at 1200 to 1350°C. The impurity atoms diffuse to the surface of Nb and are bound by a thin layer of the getter material deposited on the surface. Simultaneously the getter layer protects the Nb against impurities from the furnace vacuum.

In present high λ Nb-materials typical metallic contaminations are brought down to a level below 10 ppm. This does not correspond by any means to an homogeneous distribution of contaminants in the material. On the contrary we have indications of preferential segregations along grain boundaries. A Gedanken-experiment may illustrate the consequences of such segregations. If a 10 ppm contamination would completely cluster in $(1\ \mu m)^3$ large regions there would be about 1000 1 µm-defects per cm^2 surface. Remembering that electron emission sites do not exceed a size of a few µm one realizes how carefully Nb surfaces have to be treated if much higher field should be reached reliably in large rf cavities with many m^2 of total surface exposed to high rf fields. For the interstitials H, O, N and C which dominate the heat conductivity of Nb, contaminations have also been brought down by manufacturers in a routine way to ~ 10 ppm. This corresponds approximately to the present "technical" detection limit of such contaminations.

The increase of λ is accompanied by a decrease of mechanical material parameters such as yield strength and ultimate tensile strength which can be insufficient for the mechanical stability of large sc cavities. It becomes also increasingly difficult to confine grain sizes to a range of 30-50 µm (ASTM 6 ÷ 7) which is necessary for spinning and deep-drawing of cavities. Industry has succeeded in providing sheet material with RRR > 250 and yield strength > 100 N/mm^2.

3. SURFACE DIAGNOSTICS, INSPECTION AND REPAIR METHODS

From the beginning the progress of sc rf-cavities has been linked to the progress of diagnostic methods [16]. Of particular value are temperature measurements of the outer walls of sc cavities because each energy loss mechanism finally leads to an increase of the cavity wall temperature. In this way a detailed insight in the inner life of the cavity (and seen with the eyes of the rf!) has been made possible.

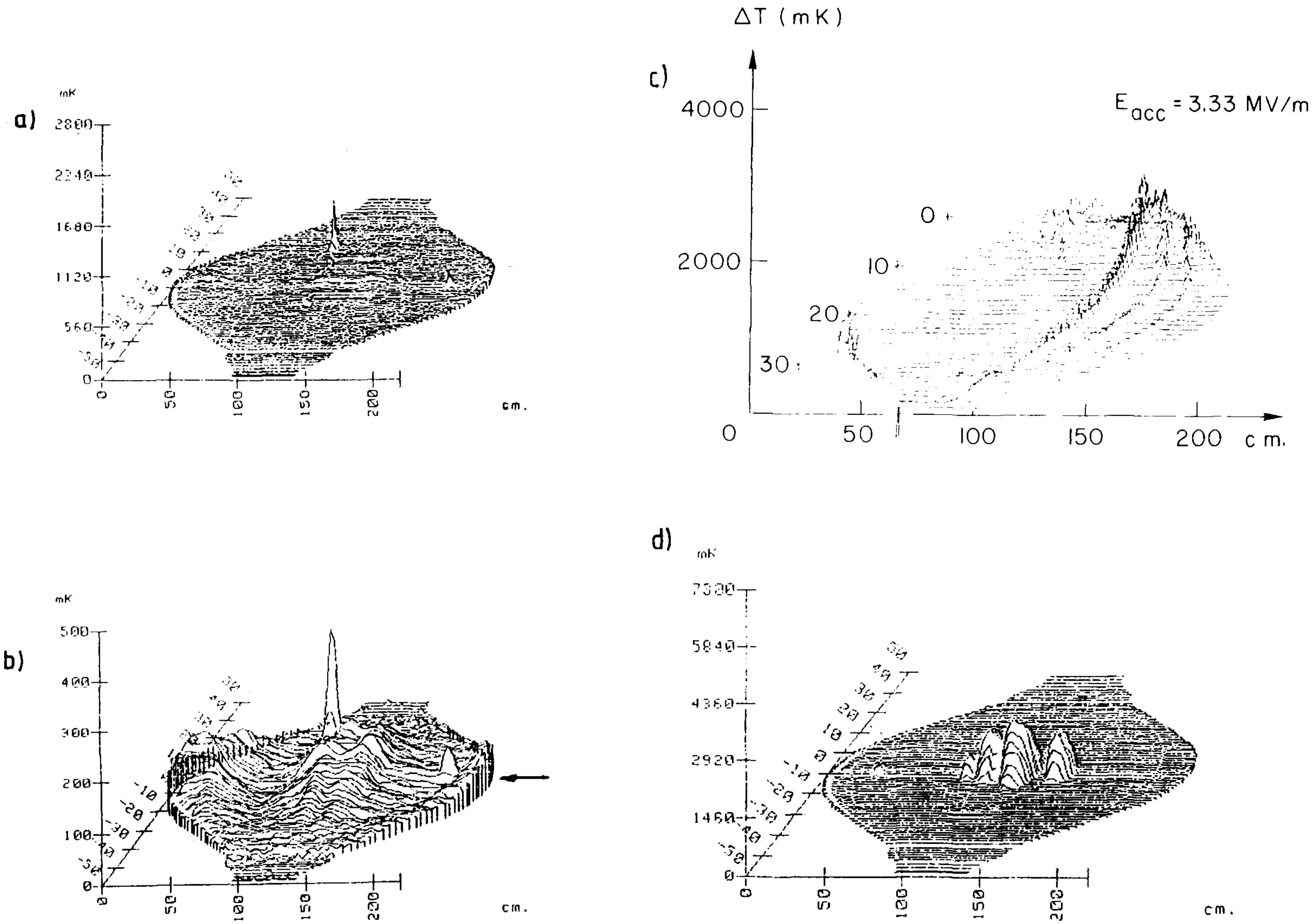

Fig. 2 Temperature maps of a 500 MHz monocell cavity of the shape shown in Fig. 1. The surface of the cavity is plotted as a "geographical" map with temperature increases as "peaks".

(a) A localised defect with increased rf losses.
(b) Same as (a) enlarged, the rf losses due to the earth magnetic field are now visible.
(c) Losses due to field emitted electrons. Electrons are accelerated and heat up the cavity wall along the azimuth of the electron source.
(d) Losses due to multipactor at the equator of the cavity.

Temperature mapping [16] with sliding sensor (temperature dependent resistor) systems located at the outer cavity walls and immersed in a bath of subcooled helium have made it possible to detect, visualize and measure quantitatively the various loss mechanisms (Fig. 2). Its role in the understanding of these losses, their nature and distributions, of defect classification and of electron emission has been invaluable. It can be foreseen that refined temperature mapping layouts will continue to play a decisive role for a further increase of cavity fields and quality factors. On a more practical side temperature mapping has been used to localise surface defects, an essential requirement for eliminating them afterwards by mechanical or chemical treatments.

During the last years efforts have been directed towards a better insulation of the temperatue sensing elements against the surrounding LHe bath. In this way a higher temperature sensitivity ($\Delta T \leq 0.1$ mK) and work in superfluid He was made possible. Systems using smaller sensors and faster read-out have also been developed [22, 23].

Already at an early stage attempts were made to combine T-mapping with X-ray mapping for the study of field emission. Small solid state X-ray detectors operating at LHe temperatures have been used.

However, one should keep in mind that temperature mapping needs very complex and sophisticated equipments and that it can only be applied to cavities operating in a liquid helium-bath. In addition some cavity shapes (especially the ones needed for heavy-ion acceleration) do not lend themselves easily to temperature mapping. Therefore inspection methods which can be applied to wall materials and cavities at room temperature (and before the first cold measurements) are highly desirable, especially for large scale applications.

At present direct visual inspection of Nb sheet material, of cavity half-cells and of complete cavities after welding is almost exclusively the method used. Present equipments using the naked eye or a telescope (Fig. 3) allow one to detect surface and welding defects down to about 50 µm diameter. This is sufficient to reach in a reliable way accelerating fields of the order of 10 MV/m in high-λ Nb material. Systems allowing an inspection of cavities with a "microscope" located near the inner cavity surface, preferably with stereoscopic view and with adequate illumination could increase the detection limits considerably. Optical equipment with CCD devices would offer the flexibility and compactness necessary for this task especially in smaller cavities. Modern image processing such as fast Fourier transforms and the use of TV-screens for display and storage would be highly desirable. Any mechanical contact with inspection devices and the inner surfaces of a cavity has to be carefully avoided, therefore the inspection system should include computerized support .

A non-destructive inspection method for sheet material used for fabrication of cavities is at hand with the Scanning Laser Acoustic Microscope (SLAM) [24], an acoustic microscope with ultrasonic visualisation and a scanning laser beam as a point ultrasonic wave detector. Prototypes have already been developed and tested on flat Nb-sheets. It is hoped that a spatial resolution of 25-50 µm can be realized. Scanning speeds allowing inspection of ~ 1 m^2 within 5 min. have already been attained. Defects can be detected at the surface and in the bulk. The method can also be used to characterize general material properties like RRR, grain size or non-uniform recrystallisation. More experience has still to be gained for detecting small isolated defects rapidly and safely.

It is tempting to combine inspection devices for complete cavities of the kind described above with repair devices. Repairs of localised defects have been made by mechanical methods such as grinding and milling, and by local chemical treatments such as chemical polishing or electropolishing [25]. Reliable repairs become extremely difficult in long multicell cavities and are nearly impossible to do in high frequency cavities where iris openings are small. Laser devices [26] may provide a more elegant solution for evaporating or "spreading" out localised defects. It is known that short, high power pulses can produce a plasma of the surface which can be heated up and cooled down so fast that oxidation of Nb under air (or under a protective gas) would be tolerable. A computerized handling device would be necessary for performing this task systematically in multicell cavities.

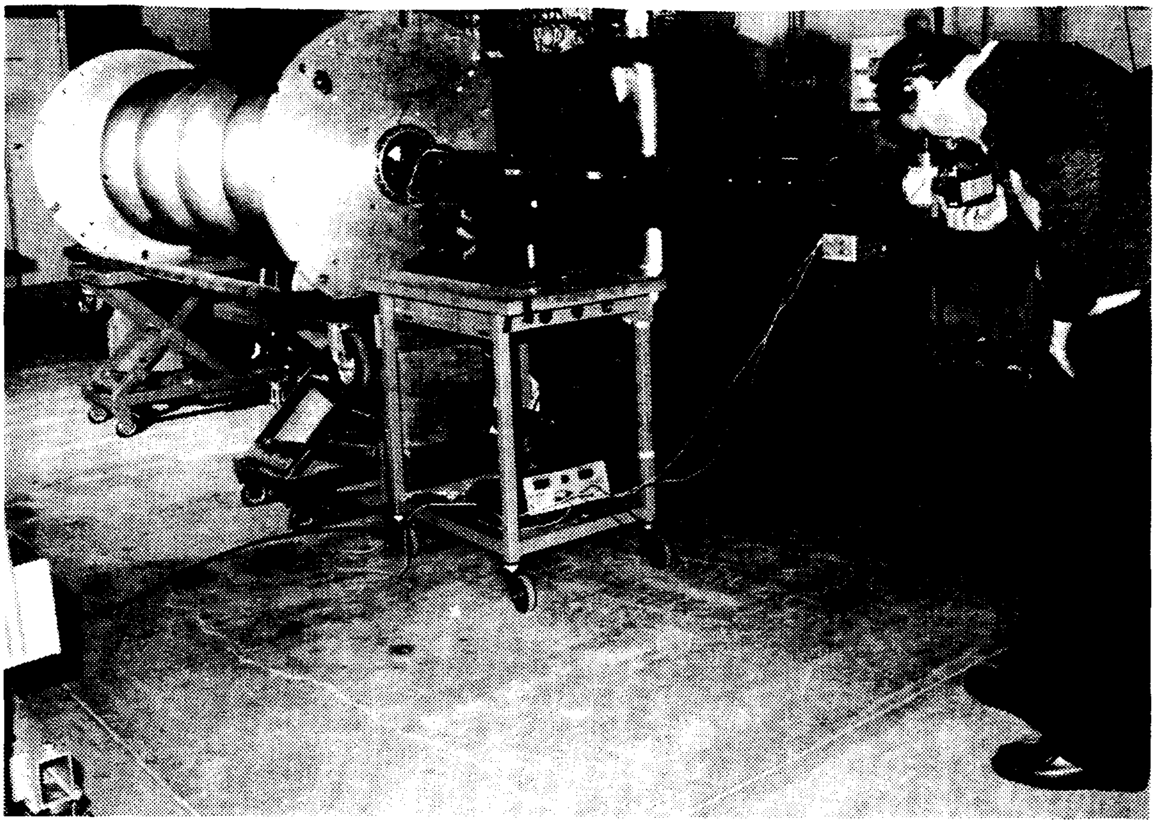

Fig. 3 Inspection device for a 4-cell LEP cavity. It is equipped with a telescope and with an adjustable mirror. Illumination at different angles is very useful.

4. SHAPING AND WELDING OF SC CAVITIES

Niobium has shaping properties in many respects very similar to the ones of Cu. For the production of cavities the normal shaping processes like rolling, deep drawing, coining or spinning have been used extensively and have given satisfactory results. The welding of shaped pieces introduces a process which is particularly liable to produce surface defects. Even a complete remachining of welding seams cannot always guarantee perfect results because they may be interspersed with voids and segregated contaminations.

Already at an early stage one has investigated the forming of single and multicell Nb cavities in such a way as to avoid weldings altogether or at least in high-field regions. Hydroforming [27] has been considered a promising approach for some time but the many intermediate annealing steps needed, expensive and complicated forming dies and a poor finish of inner surfaces have discouraged further attempts. The progress in welding of Nb-cavities has decreased furthermore the motivation for such integral shaping methods.

Contrary to Nb cavities hydroforming has been successfully applied to Cu cavities [28,29]. Because of the interest for low-cost cavities mono and multicell cavities extruded from ready-made OFHC copper tubes were produced. Three forming and thermal cycles were needed and resulted in excellent mechanical tolerances. Niobium-sputtering of those cavities was applied for hydroformed single-cell cavities with good success. Recently hydroforming has also been applied to a large 4-cell, 352 MHz cavity of the LEP geometry.

Electron-beam welding of Nb cavities has been pushed by now to a quality level and reliability which is satisfactory for large "multicell" cavities [30]. Welding is often performed in a two-step procedure: an outer (nearly) through-weld followed by an inner cosmetic weld with a defocused electron beam. Another method uses "rhombic raster" welding [31]: the beam is rapidly scanned across the welding plane in a rhombic pattern avoiding vapour column penetration and associated defects inside the Nb. Two-step welding always presents a danger of void formation between the outer and inner welding seams which may in addition be "opened" by chemical polishings.

For low frequency cavities with large iris openings welding with an internal gun presents definite advantages [32]. A full penetration of the weld is not essential and much lower beam powers are sufficient which decreases the danger of damage in case of gun failure or errors. A larger range of welding parameters can be tolerated. Welds can be of higher quality at the side where the electron beam impinges, in particular there is less danger of projections. Mounting rigs can be simpler and welding of multicell cavities in a single pumping cycle becomes easier. A horizontal position of the electron beam increases seam quality by a better stabilisation of the welding pool. In Fig. 4 typical welding layouts used at CERN are shown.

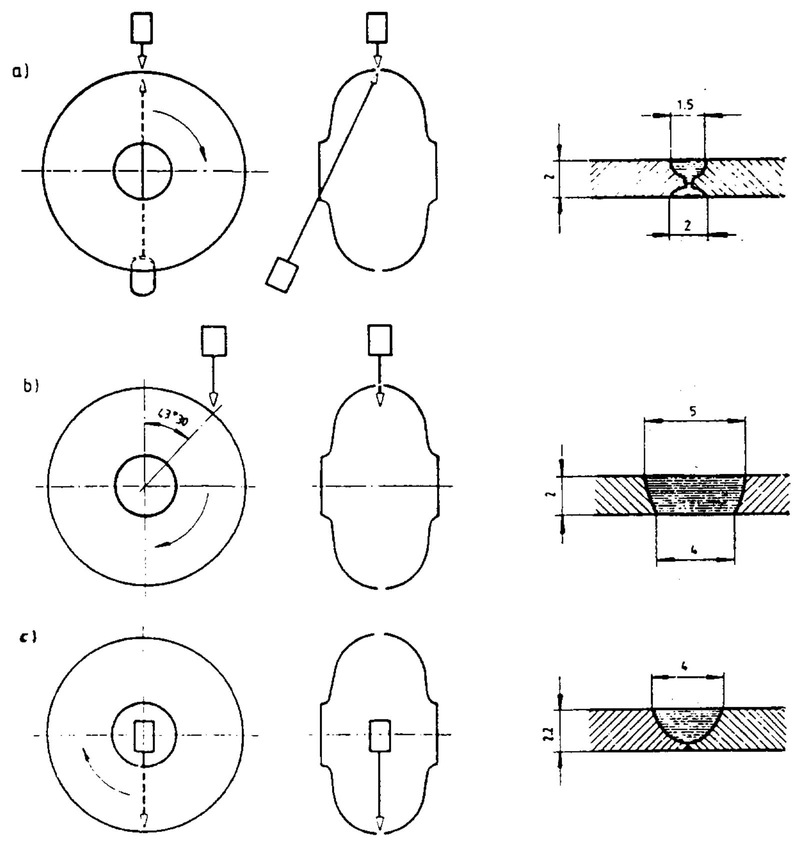

Fig. 4 Methods for electron beam welding of Nb cavities. (a) External-internal.(b)External welding only: the angle of 43° is chosen for an improved stabilization of the welding pool. (c)Welding by internal gun. The shape and size of the welding seam are also shown.

Many attempts have been made to apply TIG [25] welding to Nb cavities, mainly because of its inherent flexibility, because of less stringent mechanical tolerances and since vacuum vessels are not required. However, it has not been possible up to now to reach a degree of reliability comparable with the one of electron-beam welding. TIG welding has been applied successfully to smaller Nb parts not exposed to high rf fields (like rf couplers). Laser welding has not yet been applied widely to the fabrication of sc cavities.

Joining of Nb parts with other materials like stainless steel and Cu is extensively used and can considerably facilitate construction problems. Typical examples are vacuum flanges and waveguide flanges for main and higher-order mode couplers. Besides the normal UHV properties, flanges have to withstand low-temperature operation, repeated thermal cyclings from hundreds of °C to a few K and they must not develop magnetic fields above a few mG which may influence the rf losses of adjacent Nb surfaces. Joining of Nb with stainless steel flanges has been achieved by brazing in vacuum furnaces with Cu-Au and Cu alloys [32]. With adequate preparation and a furnace vacuum better than 10^{-4} mbar at 960°C very reliable joints have been produced. Explosive bonding of Nb to stainless steel is another method which has been used e.g. for the fabrication of waveguide flanges [25]. For the joining of Nb to Cu, electron beam welding has been successfully applied [32].

We also mention the joining of Nb, stainless steel or Cu parts to (ceramic) windows for coaxial and waveguide couplers and feedthroughs. Such elements are omnipresent in all warm and cold tests of sc cavities and in the past their reliability has often been insufficient. The development of economic, reliable rf windows and feedthroughs using Al_2O_3 and withstanding temperature shocks, operation at LHe temperatures and fulfilling the requirements of UHV, is now well mastered.

5. SURFACE TREATMENTS [33,31]

In addition to the cavity material and welds, treatments of all inner surfaces exposed to high rf fields are of prime importance for obtaining good cavity performances. Requirements for high fields and low rf losses require different surface characteristics: fields are mostly limited by well-localised defects or electron emitters whereas rf losses are more influenced by the overall nature of surface and/or by many small defects.

Surface treatments of cavities start generally by the removal of damage layers (50-100 μm) due to shaping, machining and welding. For the following surface treatments there exists today general agreement but procedures may vary from one laboratory to the other and from one cavity size and geometry to the other. Furthermore, technical feasibility questions of reliability, security and economics have to be taken into account, particularly for large scale applications.

For Nb cavities a chemical polishing in a bath of concentrated HF, HNO_3 and H_3PO_4 followed by a thorough rinsing with demineralised water, alcohol etc. and by a drying under dust-free conditions is considered necessary. Dedicated installations are essential and the trend goes to automatic installations where large numbers of cavities can be prepared and treated in a way largely independent of human interventions and under reasonably clean conditions (Fig. 5). The number of parameters governing such treatments is considerable and requires a very careful planning and testing of large installations. We mention the purity of bath constituents (very often p.a. quality is recommended), bath composition, bath temperature and saturation, flow rates and agitation (influencing the formation of viscous layers at the surfaces), removal of gases produced during treatments and avoidance of gas pockets, filling and emptying times, fast neutralisation of acids at inner surfaces, final pH of rinsing waters, etc. Security aspects like overflow facilities and emergency drains have to be integrated in the system. Non-Nb parts have to be protected carefully from the very agressive acids used. In general these operations are not attempted under dust-free conditions.A major concern is a rapid emptying and neutralisation of acids at the cavity walls. Already contact with air for a few seconds can lead to the formation of non-soluble Nb salts which are hard to remove by subsequent rinsings.

The importance of adequate rinsing and drying cannot be overstated. Dust-free conditions (class 100) are of utmost importance. Great care has also to be taken for the rinsing liquid quality and cleanliness. At present dust-free ultrapure water (ρ = 18 MOhm x cm, standard of semiconductor industry) is widely used for final rinsings. It may turn out that for the preparation of rinsing water additional steps may be useful e.g. improved sterilisation, removal of organic molecules and of species not removed in normal ion exchangers (e.g. humic acid, Fe, SiO_2 ...). Rinsing with high pressure water (~ 100 bar) has already been proposed at an early stage [34]; recent tests are very promising and one should include this method in the sequence of treatments for high performance cavities. A more detailed knowledge of cleaning steps applied for electronic microcircuits will be of help but one has of course to judge if the application of methods used for small planar elements to large partly closed cavities is not prohibitive. More studies on the rinsing procedures would be desirable and other liquids may result in better surface characteristics with respect to electron emission and rf losses.

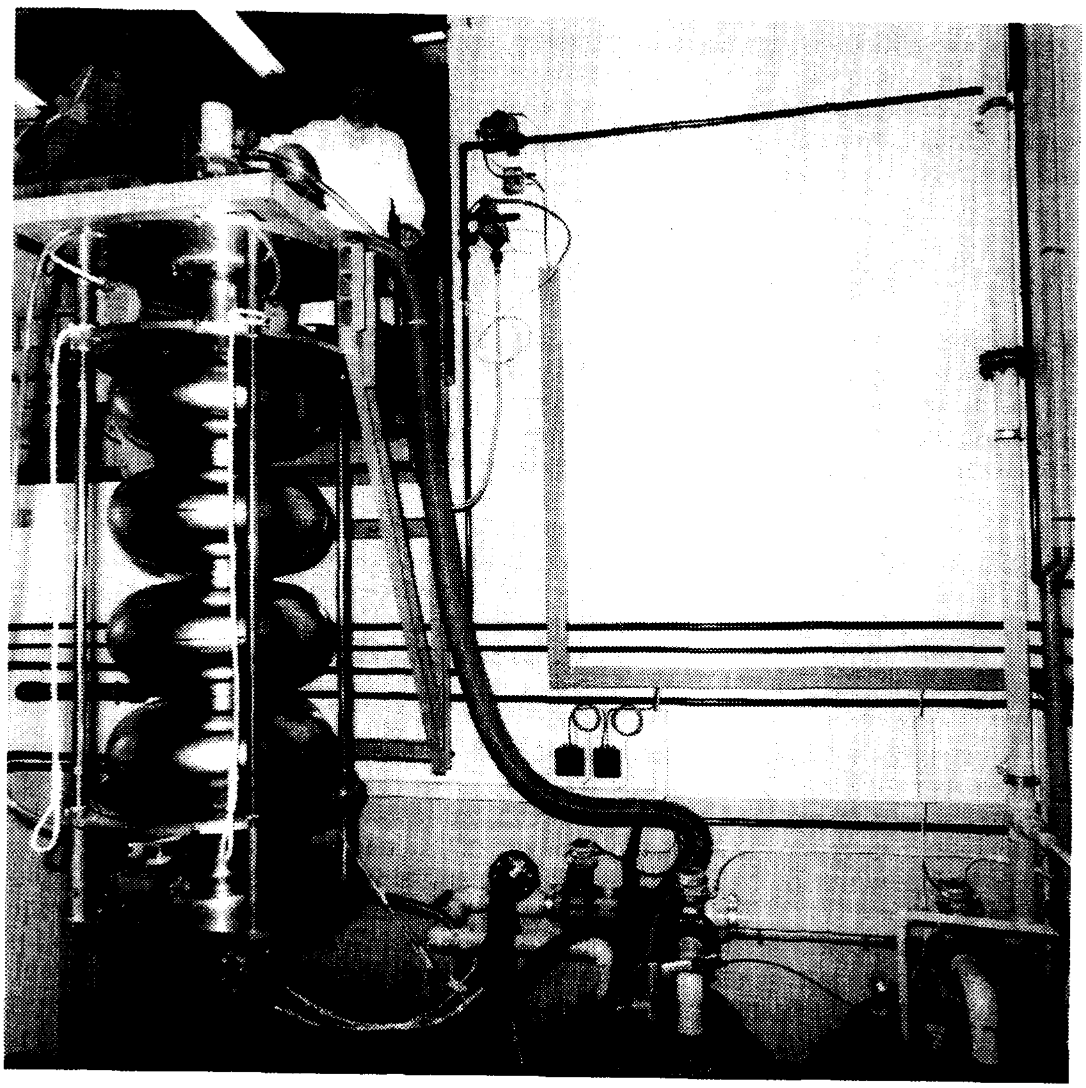

Fig. 5 Installation for degreasing, chemical polishing and rinsing of 4-cell Nb cavities for LEP. The installation and working cycles are controlled by a microprocessor.

Drying of cavities under strictly dust-free conditions is another essential step. Sometimes a sequence of water and alcohol rinsing is used to decrease drying times. Drying of water residues in a dust-free room (at least class 100) has been used but leads to very long drying times with a danger of contaminating cavity surfaces by chemical components passing through the dust filters of the clean room. Drying with a roughing pump is often applied instead but one has to take great care that an oilfree vacuum at the cavity is guaranteed.

In summary, for the final surface treatments and assembly of cavities, the standards used today in semiconductor production should be extended to very large systems consisting of many cavities with their auxiliaries and with a total length of many metres.

The way towards higher fields may require more sophisticated surface treatments. We mention in particular electropolishing which can produce very smooth surfaces with less danger of dust particles clinging to surface asperities, and better conditions for defect inspection. The most powerful method may turn out to be a high-vacuum, high-temperature treatment. The benefits of such treatments are not questioned but one hesitates to apply such complex treatments to large Nb cavities because of the costs of large furnaces, the problems of mechanical stability of cavities at high temperatures and the difficulty to obtain clean, dust-free working conditions. If temperatures above 1100°C prove necessary such treatments cannot be applied to Nb/Cu cavities, and brazing of stainless steel flanges to the cavity ports will not be possible.

High power rf processing with power levels of a few hundred watts has been used successfully for increasing field levels and quality factors in low-β structures. Very recently an extension of this method to (pulsed) power levels of many hundred kW in 3 GHz cavities has given considerable improvements in cavity performances [35]. This method which is thought to eliminate defects and field emission sources by explosive overheating has the benefit of an "in situ" treatment and may even be used for repair after vacuum accidents.

6. CAVITIES COATED WITH THIN SUPERCONDUCTING LAYERS

The earliest sc rf cavities used as a cavity material copper which was covered by electrodeposition with a few µm of Pb. This procedure has the merit of easy and cheap fabrication and it can be applied to complicated geometries. It is still finding use for the fabrication of low-β structures. With the advent of Nb it was also natural to consider deposition methods of Nb on Cu cavities and to profit in this way from the much higher heat conductivity of Cu (about an order of magnitude higher than that of Nb). In recent years a large effort has been initiated at CERN [36] in view of applications for LEP. Among the possible coating methods such as electrolysis from fused salts, chemical vapour deposition, evaporation, sputtering and ion implantation, sputtering was preferred for several reasons. The relatively low deposition temperature does not produce copper annealing and the energy of impinging Nb atoms is high enough to result in good adherence to the Cu walls. Because of the Meissner effect causing very small penetration depths of the rf fields ($\lambda_L \approx 50$ to 200 nm) a layer thickness of the order of 1 µm is sufficient.

Magnetron sputtering (Fig. 6) has been found particularly adequate [37]. With respect to the initially tried bias sputtering it allows higher deposition rates (~ µm/h), better adhesion, more uniform layer thicknesses and an easy extension to multicell cavities. The sputtering is done at an argon pressure of 10^{-2} to 10^{-4} mbar and it was possible to vary sputter conditions so that the RRR value of the deposited layer corresponds approximately to the minimum of the BCS surface resistance. A rather unexpected benefit of the sputtered layer is the insensitiveness of rf losses with respect to external magnetic fields, therefore the usual magnetic shielding for earth magnetic field is not necessary. The use of Cu instead of solid Nb sheet material allows a saving in material costs, which is particularly interesting for the large LEP cavities. It may also favour tube cooling for specific applications.

The cleaning of Cu surfaces prior to Nb sputtering appears to be crucial. Surface contaminations with a size of a few µm cause poor adhesion and blistering of the Nb layers. Concerning cleanliness the requirements for Cu surfaces are therefore similar to the ones for Nb surfaces.

Results obtained in a series of Cu cavities with the geometry of the sc LEP cavities [37] were so encouraging that it was decided to use magnetron sputtered cavities for the upgrading of LEP and orders were placed at three European manufacturers. The design values for accelerating fields and quality factors could be raised from 5 to 6 MeV/m and from 3 to 4 x 10^9 respectively.

As expected, under normal preparation and operation conditions no thermal breakdowns were observed. This can be an advantage for large scale systems where many cavities may be powered by a common klystron. Cavities which in the course of operation develop defects (e.g. by dust transport along the beam vacuum chambers or by vacuum failures) may be operated at the expense of slightly increased rf losses.

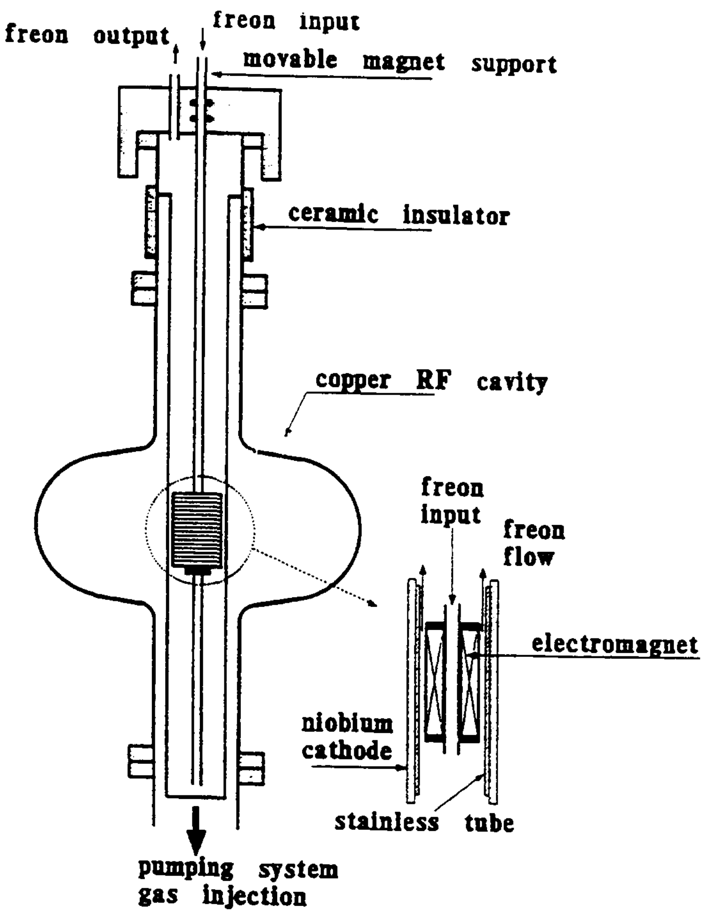

Fig. 6 Magnetron sputtering of a Cu cavity with a Nb cathode and a movable magnet (courtesy C. Benvenuti, CERN).

It is expected that a better understanding and more advanced deposition techniques can reveal other interesting properties of thin Nb layers which then can be engineered more precisely to the specific needs of sc cavities. Another aspect is the production of intermediate layers improving the sc layer properties (e.g. adhesion) and the manufacturing of protective layers. Sputtering of Nb in more complicated geometries such as coupler ports, couplers and low-β cavities is under development [38] and will certainly find numerous applications. The development of deposition techniques should also advance the application of high T_c alloys such as Nb_3Sn and NbN or the new high-T_c superconductors [39,40].

Finally it should be realised that the use of sc layers in cavities presents a challenge for large surfaces which have to be defect free to an extent rarely encountered up to now. As another example one may mention the use of ZnS films in electroluminescent display devices [41] of many m^2 size. For industrial applications films have to withstand internal fields up to

150 MV/m. The number of defects (pin holes) with a diameter exceeding 30 μm can be kept below one defect per m^2. These defect numbers are comparable to the ones we would like to achieve in large, high performance cavities.

ACKNOWLEDGEMENTS

I would like to thank my colleagues from CERN for many fruitful discussions and for information, in particular, D. Bloess on inspection methods and surface treatments and E. Chiaveri on fabrication methods.

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