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STATUS AND APPLICATIONS OF $\beta = 1$ SUPERCONDUCTING CAVITIES

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This paper sketches the most recent trends of the R&D and applications of RF superconductivity to $\beta = 1$ accelerators.

KEY WORD: Superconducting RF

1 INTRODUCTION

Superconducting cavities have now been used in many accelerators, e.g., large storage rings at CERN, KEK and DESY, electron linacs at Stanford, Darmstadt, Saclay-Orsay and CEBAF, or free electron laser drivers. Experience gained during the building of these machines strongly suggests that RF superconductivity is already a mature technology, even if it is still far from its limits. New applications are now being envisaged, both at the high luminosity and at the high energy frontiers of the accelerator technology.

The physics and accelerator applications of RF superconductivity have been excellently reviewed by many authors. (References 1–9) The present paper will concentrate only on the highlights and on the most recent developments in the field. Included topics are large scale fabrication, thin films, surface preparation and cavity performance level. Despite its importance and its close connection to cavities, the problem of couplers and windows has been deliberately omitted in this article. The most important issues of the R&D on superconducting cavities, i.e., the quest for high gradients and reduced RF dissipation, will be reviewed.

2 HIGH GRADIENTS

The accelerating gradients available in Niobium superconducting cavities have been in considerable progress recently, increasing by as much as 50% during the last two years. This progress may be ascribed to the conjunction of at least four factors: improved

TABLE 1: Summary of the laboratory best results. ep = electropolishing; bcp = buffered chemical polishing; ht = heat treatment; hpp = high peak power processing; wr = water rinsing (low pressure); hpr = high pressure water rinsing.

Laboratory	Cavity type	Treatment	Eacc (MV/m)	Epeak (MV/m)
KEK	508 MHz, 5 cell	ep	15	30
	1.3 GHz, 1 cell	ep + ht	30	54
CERN	352 MHz, 4 cell	bcp	>10	>22
Cornell	1.5 GHz, 1 cell	ht	30	60
	1.5 GHz, 5 cell	hpp	27	71
	1.5 GHz 6 cell	ht	20	40
	3 GHz, 2 cell	ht + hpp	30	100
	3 GHz, 9 cell	ht + hpp	19.5	41
DESY	500 MHz, 5 cell	bcp	8.5	21
CEBAF	1.5 GHz, 1 cell	bcp + ht + hpr	28	65
	1.5 GHz, 5 cell	bcp	20	51
	1.5 GHz, 5 cell	bcp + ht + hpr	21.5	55
Darmstadt	3 GHz, 20 cell	ht	20	~50
Saclay	1.5 GHz, 1 cell	bcp	23	50
	1.5 GHz, 1 cell	bcp + ht	28	61
	1.5 GHz, 3 cell	bcp	20	40
	1.5 GHz, 5 cell	bcp	18	40
Wuppertal	3 GHz, 1 cell	ht + bcp	27	68
	3 GHz, 5 cell	ht + bcp	22	66
	3 GHz, 9 cell	ht + wr	17	36
Los Alamos	3 GHz, 1 cell	bcp	22	78
	800 MHz, 1 cell	bcp + hpr	20	52

cleanliness standards (Reference 10), the development of RF processing techniques like High Peak Power Processing (References 11–16), the availability of higher purity niobium (Reference 17), and the generalization of the heat treatment of the cavities (Reference 18–25). A summary of the laboratory best results is given in Table 1.

Accelerating gradients are still limited by two phenomena: quenches and field emission. The relative importance of these two causes varies from laboratory to laboratory, and depends on the purity of the niobium used, as well as the degree of cleanliness of the surface preparation. The impression gathered from a systematic compilation of the results worldwide is that roughly 50% of the gradient limitations are due to quenches, while the remaining 50% come from electron emission.

The maximum electric field that can be obtained without field emission depends on the area exposed to the field. Surface fields higher than 100 MV/m have been

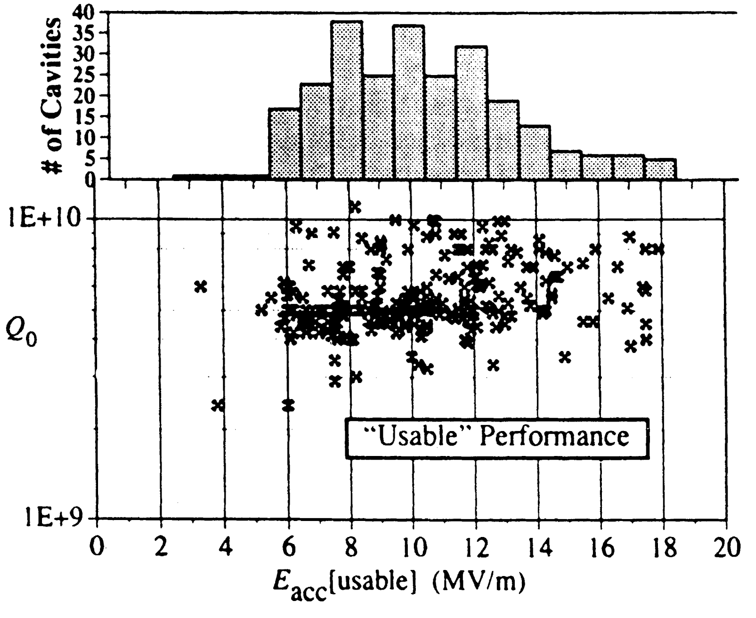

FIGURE 1: Systematics of the 1.5 GHz, 5-cell cavities from CEBAF (from Reference 27).

obtained without electron emission on areas of the order of 1 cm^2 (Reference 26); surface fields of 50 MV/m have been reached often at about 1 GHz on single cell accelerating cavities, and 35 MV/m on 3- or 5-cell cavities. The largest data base comes from CEBAF (5 cell, 1.5 GHz, T = 2 K), (Reference 27), (Figure 1). The results are very encouraging, since nearly all the CEBAF cavities tested so far exceed by large amounts the design value: the average surface field obtained is close to 20 MV/m. Moreover, there is no significant degradation of usable gradient of the CEBAF cavities between their test in a vertical cryostat and their use in the accelerator (Figure 2). Similar gradients have been achieved in a much smaller test series on 9-cell cavities at Cornell and Wuppertal (3 GHz, 1.8 K). There is much confidence that surface fields as high as 30 MV/m can be obtained reliably, without electron emissions in 9-cell structures at 1.3 GHz. With the ratio $E_{surface}/E_{acc} = 2$ currently obtained in present day cavity designs, this corresponds to accelerating gradients of 15 MV/m.

3 FIELD EMISSION

It is now recognized that field emission in cavities is due to surface defects of micrometer size, causing electron emission from the surface and subsequent loading of the cavity (Reference 28). Recent systematic studies have confirmed that deliberate contamination of the cavity surface by conducting, micrometer sized particles results in

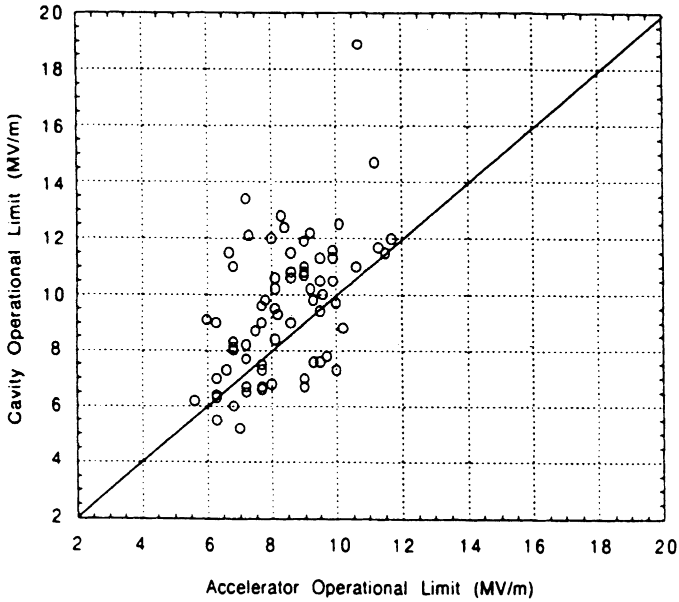

FIGURE 2: Comparison of the performance of CEBAF cavities in vertical test cryostat and in the actual accelerator situation (from Reference 9).

heavy field emission (Reference 29). Insulating particles seem to be much less dangerous. The relevance of this information for the case of SC cavities may be discussed, but a rigorous cleanliness of the cavity surface seems to be an indispensable prerequisite to avoid field emission. So far, efforts have concentrated on the prevention of particulate contamination during the chemical treatment of the cavity, and during the subsequent rinsings. Automated chemical treatment facilities have been developed, in order to minimize human intervention during the process. Their main philosophy is to treat the cavity as a pipe, etched by a continuous flow of recirculated, filtered, thermostated acid flow, then rinsed and dried without opening the cavity (Reference 10). Advanced cleaning techniques have also been applied in various laboratories. Among these, high pressure rinsing seems to be most promising (References 30–32), (Figure 3). Its idea is to use the mechanical action of a high speed water jet to remove micron sized particles adhering on the surface (Reference 33). Other techniques, like megasonics, dry wiping, ...have been tried in a less systematic manner, with promising results (References 22,34).

Particulate contamination also arises during assembly and pumping of the cavities. The assembly steps involve unavoidable contact and abrasion of metal parts, liable to generate metallic dust particles and field emission. This problem has received much less systematic attention than the problem of cleanliness during the wet process. The success of CEBAF cavities, and their quasi absence of performance degradation between vertical and horizontal tests might be due in part to the hermetic sealing of the cavity pairs after assembly. This idea

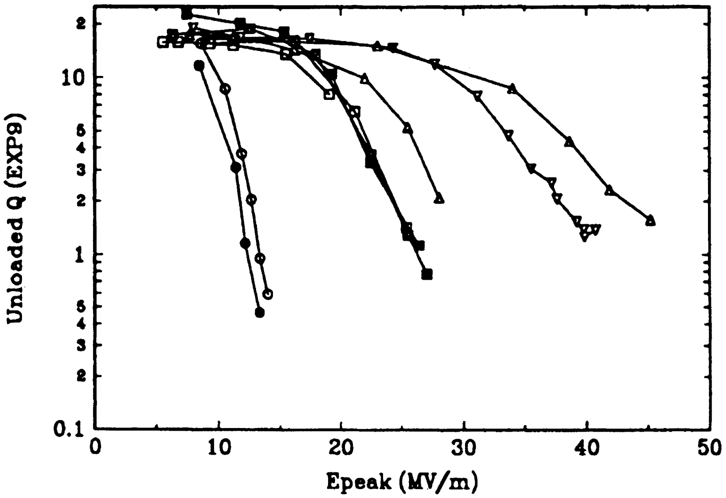

FIGURE 3: Benefits of the high pressure rinsing (HPR) at Los Alamos (from Reference 31). Q vs peak surface field at 2 K. a) cavity performance after exposure to room air (circle), b) Cavity performance after first HPR (box), c) Cavity after second HPR (triangle).

has now proven its validity and should be generalized. Of course, it does not solve all the problems of assembly: this leaves room for future R&D, and hopes for further improvement.

Another possible remedy to cure field emission is the firing of the cavities. Firing of niobium under vacuum at very high temperature volatilizes or dissolves most chemical species and yields extremely clean surfaces. When applied *in situ* to Niobium samples (i.e., not reexposed to air and dust after the firing), this treatment is a very effective suppressor of field emission (References 28,35). Its application to cavities improves drastically the accelerating gradients (References 18–25), but this improvement can be fully realized only if the assembly stages which occur necessarily after the firing do not contaminate too much the cavity surface.

4 RF PROCESSING

High peak power processing (HPP) is another possible recipe for suppressing field emission in superconducting cavities. It consists basically in sending a RF pulse intense enough to "burn" the electron emitters, during a time short enough to prevent a quench (References 11–16). A two-cell, 3 GHz cavity reached a maximum surface field of 100 MV/m at Cornell after such a high peak power processing. This is certainly a very promising technique, but its applicability to the real case of an accelerator is not demonstrated yet. If HPP is to be applied on a cavity already installed in an accelerator, the coupling line will have to withstand the power necessary for the treatment (of the order of 1 MW/m, Reference 16). This requirement cannot be met in most accelerators. However, "moderate power processing" (a few kW/m) is much more readily applicable *in situ*, has proven its validity (Reference 36), and is used, for example at CEBAF and on MACSE. On the other hand, the usefulness of HPP as an "ex situ" treatment is not yet fully established, because it remains to be seen to what extent the benefit of the treatment is kept after a dismounting of the cavity and a new exposure to air. The answer to this question will probably depend on the degree of cleanliness of the treatments following HPP. Again, attention should be given in priority to the weakest link of the chain!

5 QUENCHES, AND THE PROBLEM OF NIOBIUM PURITY

The limitation of gradients by quenches (i.e., thermal instabilities of the cavity initiated by heating defects) has been a severe one in the past. It has been demonstrated that the starting point of the quenches are localized sources of heating, for example normal conducting inclusions. Improved cavity fabrication techniques, featuring sheet and cavity inspection, electron beam welding and surface polishing, have significantly reduced the number of large defects. These progresses already restrict the occurrence of quenches to a reasonable rate of about 20% for Nb single cell accelerating cavities in the GHz range with gradients smaller than 15 MV/m. The important parameters governing the thermal behaviour of the cavity are the defect size and resistance, and the thermal conductivity of the cavity wall (References 37,38). High temperature vacuum annealing of the cavity gives the possibility of purifying the Nb, e.g., by solid state gettering with Titanium, thereby increasing its thermal conductivity and the quench threshold of the cavity (Reference 20). The heat treatment at 1400°C has also proved to reduce the electron emission from the surface (References 28,35). It is striking to see that in all laboratories, the highest gradients have been obtained with fired cavities (Table 1). For example, accelerating gradients as high as 30 MV/m have been reached at Cornell on single cell cavities at 1.5 GHz after heating the cavity to 1300°−1500°C (Figure 4). Unfortunately, the cavity heat treatment is a very delicate, expensive and time consuming process. After heat treatment, the mechanical properties of the niobium are severely deteriorated. In most cases, this degradation should be tolerable, but very few fired cavity have been used in actual accelerators. Moreover, the preservation of the cleanliness of the cavity surface after heat treatment is very difficult to achieve: a new check of the field profile, maybe followed by a new chemical etching or a water rinsing, are considered useful after a heat treatment. This probably reduces to some extent the benefit of the furnace step from the electron emission point of view. Nevertheless, it remains a very interesting R&D tool, which should be investigated further.

It has been noticed at Cornell that if gradients continue to improve, even defect-free cavities might be limited by a global thermal instability, caused by the residual surface resistance of the material (Reference 39). The threshold for the onset of this "global" quench is lower for higher frequencies, and is of the order of $E_{acc} = 30$ MV/m for state-of-the-art Nb cavities at 3 GHz. Here again, the improvement of the thermal conductivity of the material will be indispensable to go beyond this value.

A significant proportion of the CEBAF cavities are still limited by quenches. This probably means that the cavity chemical treatment and handling are done in very clean conditions, thus preventing field emission. Another consequence is that these cavities might

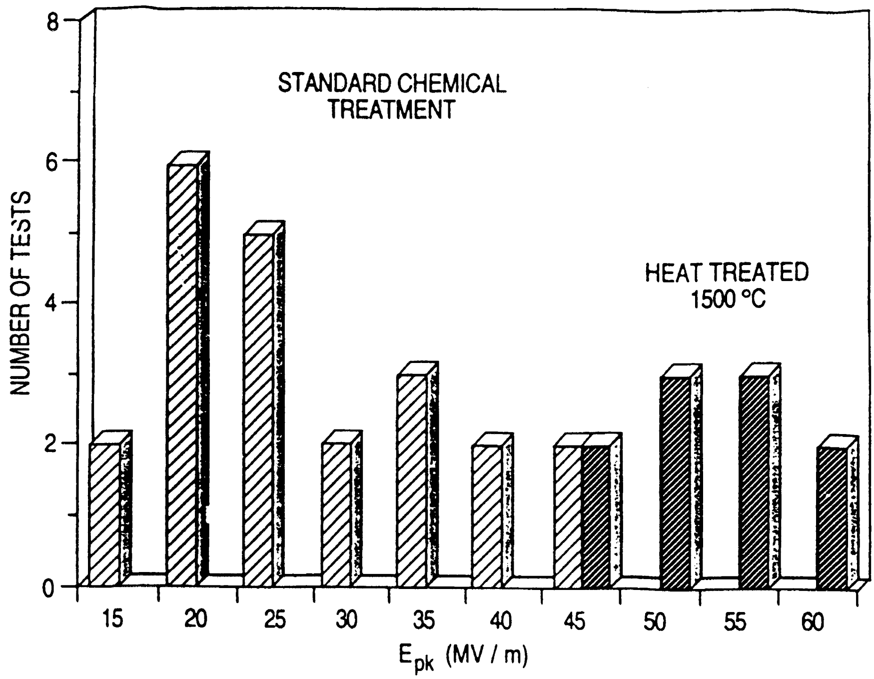

FIGURE 4: Benefits of the heat treatment on single cell niobium cavities at Cornell (from Reference 1).

reach higher gradients after a purification improving their thermal conductivity. Definitely, a niobium purity of RRR 200 is not sufficient for high gradient applications!

In the far future, it is probable that the purification of Niobium will be achieved at the stage of the Nb sheet production. A high purity Nb sheet of RRR 400 with adequate formability can already be ordered from industry. Prospects of further improvement are good (Figure 5), since very high purity Niobium (RRR > 600) is in principle available from Russian industry (Reference 40). However, it is known that the forming of niobium sheet introduces a large density of dislocations in the material, thereby reducing its RRR and thermal conductivity. This might reduce somewhat the advantage of using very high purity Nb sheet as a starting material. This problem has been largely overlooked in the past, due to the difficulty of measuring the RRR of a cavity already formed into shape. In this context, heat treatment of the material at the stage of the half cell production remains an interesting option.

6 PROGRESS IN Q VALUE

It is essential for the success of many kinds of superconducting accelerators to minimize the RF power dissipated in the cavities. Substantial progress has been made during the past two years. The main cause of non-reproducibility of the cavity Q value, i.e., hydrogen contamination, has been understood (Reference 41) and eradicated to a large extent. In all

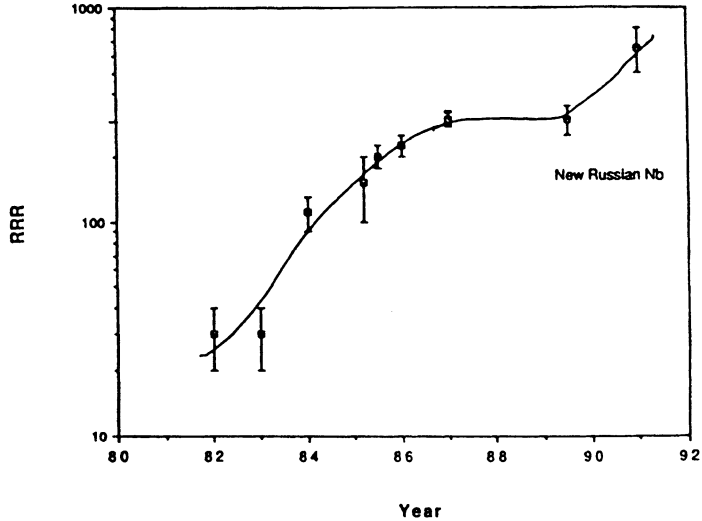

FIGURE 5: Progress on the purity of commercially available niobium (from H. Padamsee, private communication).

R&D laboratories, this effort yielded cavities with high and reproducible residual Q, with typical values as high as 2 10^{10} for Nb at 1–3 GHz. This corresponds to an average residual surface resistance between 10 and 20 nΩ. The reproducibility mentioned above now permits to gain sensitivity to residual R_{res} at the level of a few nΩ, and opens new hopes to increase the Q value still further by an improved treatment and curing of other causes of dissipation:

6.1 *Trapped flux*

The shielding level of vertical cryostats is typically 20 mGauss. This corresponds to a residual dissipation of 5–10 nΩ, i.e., a significant proportion of the total state-of-the-art R_{res} (Reference 42). At Saclay, an improved shielding of the vertical test cryostats brought the ambient field level down to 2 mGauss, and the corresponding subsequent reduction in R_{res} was indeed observed, boosting reproducibly the cavity Q to values as high as 5–7 10^{10}.

6.2 *Dissipation in the cutoff tubes*

This level of Q value also gave some improved sensitivity to other trivial causes of residual losses, like dissipation in the cavity cutoff tubes. In all $\beta = 1$ cavities, the cutoff tubes behave like waveguides below the propagation threshold, with an exponential decay of the EM field. If the tube is too large in diameter or too short in length, the field remaining at the end of the cutoff tube can cause significant losses, which can be avoided by a careful design of the cavity. The improvement in Q value observed at Saclay was in fact obtained by the conjunction of a good magnetic shielding *and* a good cavity design.

6.3 Q disease remnants

With a well designed, well shielded cavity, the necessary precautions to achieve high Q values are not too demanding; starting from the state-of-the-art, RRR 300 niobium sheet delivered by industry, a buffered chemical polishing followed by a careful rinsing seems to be sufficient. However, the additional dissipation due to niobium contamination by hydrogen should be addressed here. It has been proven that this "Q disease" could be cured either by a vacuum furnace treatment of the cavities at 800°C during 2 hours, or by a rapid cooldown of the cavities. The first remedy is inconvenient, and the applicability of the second one is not guaranteed (a rapid cooldown seems to be successful at CEBAF, however). P. Kneisel investigated in detail the Q degradation due to H contamination, as a function of cooling speed (Reference 43, Figure 6). His recent data suggest that even the fastest cooling can cause some degree of degradation. This shows that the "Q disease" problem is still open, and leaves some room for further improvement. Non contaminating chemical or electrochemical polishings of the Nb surface should be investigated in detail.

Altogether, it can be said that R_{res} in well designed, well measured superconducting cavities made from Nb sheet is *very small*. Surface resistance as low as a few nΩ have indeed been observed, for example at Wuppertal (Reference 44, Figure 7) or at Saclay (Reference 45). This corresponds to Q_{res} = 5–6 10^{10}, a value now routinely obtained in vertical test cryostat at Saclay, even with non heat treated cavities. This result has considerably clarified the list of possible causes of residual dissipation in superconducting cavities. Putting aside the three major causes already discussed, this list featured (References 46,47) dielectric losses in the Nb_2O_5 oxide layer and in the adsorbed species, normal conducting inclusions, oxide-induced surface serrations, geometrical defects like cracks, crevices or delaminations, losses in the disordered layer at the Nb-oxide interface, losses in the grain boundaries,... The order of magnitude of each contribution was poorly known: we now know from experiment that their sum amounts to less than a few nΩ for state-of-the-art, non heat treated cavities. This value can and should become a standard for vertically tested cavities. It remains to be seen to what extent the benefits of this improvement in Q value are kept in a real accelerator environment, where the demands on magnetic shielding, cavity design, and cooling speed are met less easily. If significant improvement in Q values can be obtained in real accelerators, this might permit operation of pulsed accelerators like TESLA with duty cycles larger than the ones envisaged now. The full benefit of this progress will be realized only if efforts are also made to minimize another important cause of cryogenic consumption, i.e., the static losses of the cryostats.

7 CAVITY FABRICATION

Presently, most $\beta = 1$ accelerating cavities are made from Nb sheet, and their fabrication includes forming of half cells from sheet material, and electron beam welding of the half cells. This "EB welding method" is very delicate because of the requirements it imposes on the degree of cleanliness of the surfaces to be welded. It is also time consuming and poorly suited to large scale production in industry. It involves many operations, especially

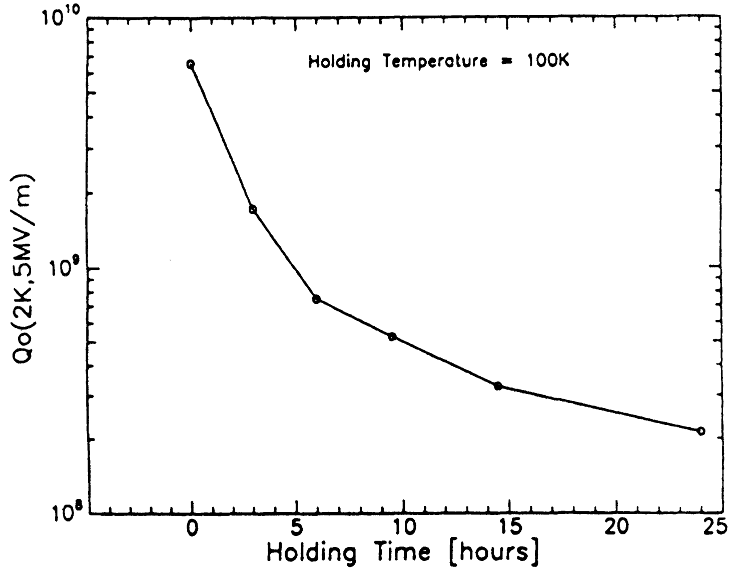

FIGURE 6: Q degradation due to hydrogen contamination: time dependence of degradation at 100K (from Reference 43).

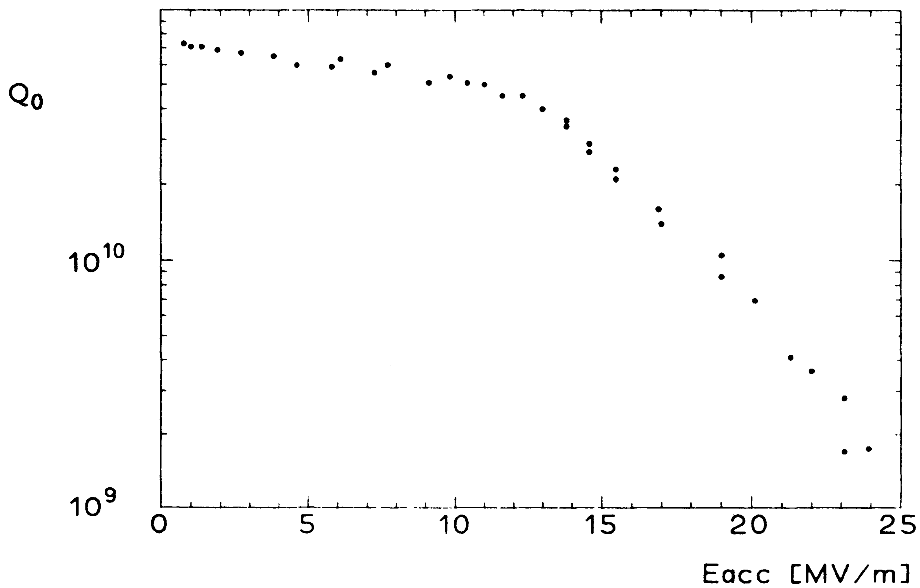

FIGURE 7: Very high Q-value obtained in a 3 GHz single-cell niobium cavity at Wuppertal (from Reference 44).

for cavities with a large number of cells. Besides, even with a very good vacuum in the EB welder, the preservation of the niobium purity at the welds becomes increasingly difficult to guarantee, if very high purity niobium is used. An alternative approach based on forming seamless Nb tubes may be promising for such cavities. The drawability of niobium seems to be sufficient for this purpose. Early tests have failed at DESY and CEBAF, but have been successful at Cornell on single cell cavities (Reference 48). However, forming of refractory metals is a very delicate process, especially if high purity material is used. It will probably involve intermediate annealings of the cavity during fabrication. It remains to be seen whether the number of annealings and the purity of the material can be maintained at an acceptable level. This technique is presently under investigation in industry (e.g., CERCA, Heraeus).

Another method of fabrication starting from one single niobium sheet has been developed by Palmieri *et al.* at Legnaro to make seamless single cell cavities, by use of a dismountable mandrel (Reference 49). Extrapolation of this method to multi-cell cavities is not straightforward, but might yield very interesting results in the near future.

In case of success, these techniques might result in a very significant reduction of costs for a large scale cavity production.

8 THIN FILMS

In cavities, the superconducting current flows in a very shallow skin depth, of the order of 100 nm. This suggests the use of a thin superconducting film deposited inside the cavity. The expected gain is threefold: a metal with good thermal conductivity can be chosen as substrate, with a subsequent enhancement of the cavity thermal stability; the substrate (e.g., OFHC copper) is cheaper than niobium sheet; the thin film may have improved superconducting properties as compared to niobium. Investigations have been made mainly with Nb, NbN, NbTiN and Nb_3Sn thin films.

CERN has developed with success the technique of Nb thin film deposition on copper for the LEP200 cavities (References 50,51). At the low frequency used for these cavities, the technology of thin films is especially attractive, since the amount of saved niobium is important. Moreover, at the temperature of 4.5 K used for LEP cavities, the BCS contribution to the surface resistance is dominant, and can be minimized by use of a niobium RRR of the order of 20, i.e., about the value obtained with sputtered thin films. The transfer of this new technology to industry has met some difficulties. The chemical treatment of the copper substrate turned out to be a most crucial point, determining the adherence of the Nb film. Local lacks of adherence resulted in "blisters", with poor thermal contact between the film and the substrate. Thermal instabilities of these blisters caused abrupt degradations of the cavity Q value. An appropriate chemical treatment, combined with a dust-free handling of the Cu substrate brought this problem under control. All three companies involved in the LEP cavity fabrication now deliver cavities with Q values and gradients above the specifications (E_{acc} = 6 MV/m, $Q_0 = 4\ 10^9$ at 4.5 K). These Nb/Cu cavities behave as well, if not better, than massive niobium ones of the same design (Reference 50). Full scale production of the cavities has now started (Figure 8), and the first assembled cryomodules arrive for qualification at CERN.

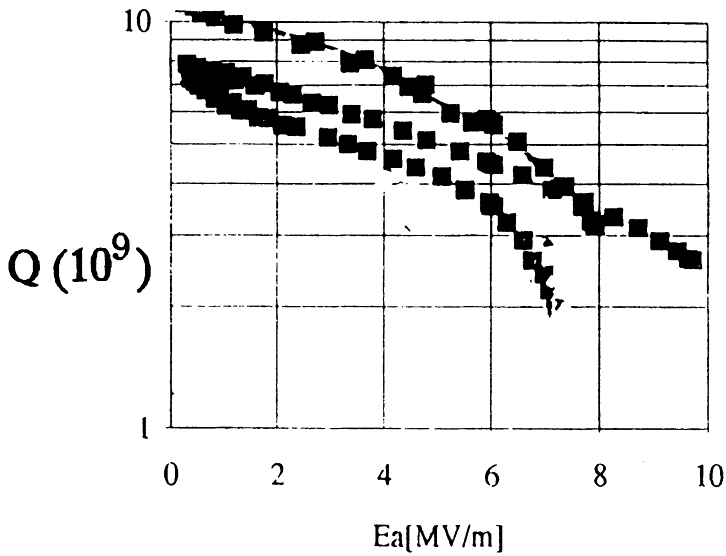

FIGURE 8: Typical Q (10^9) vs E_{acc} (MV/m) of accepted Nb/Cu cavities for LEP, as measured in vertical test cryostat (from Reference 50).

Nb/Cu cavities have also been developed at higher frequency, by a CERN-Saclay collaboration. Here again, the results are encouraging, since accelerating gradients as high as 16 MV/m have been obtained in single cell cavities at 1.5 GHz (Reference 52).

The three intermetallic compounds NbN, NbTiN and Nb_3Sn have a critical temperature of 17–18 K, and a very small surface resistance $R_{BCS}(T)$. The results obtained so far with these compounds are encouraging: as compared to Nb, a reduction of R_{BCS}(4.2 K) by a factor 10 for a NbTiN thin film sputter-deposited on copper has indeed been observed at Saclay (Reference 53); Improvement factors up to 100 have even been obtained for thermally produced Nb_3Sn thin films on Nb (References 54–56). Unfortunately, the residual surface resistance of these films is rather high (a few hundreds of nΩ at GHz frequencies), and increases with increasing RF field. Moreover, the gradients obtained are still too low for most applications. The present limitations of performance are due to imperfections in the thin film morphology, causing granular superconductivity (References 57–61). Consequently, films characterized by a larger grain size and cleaner grain boundaries should provide better RF performance. Experimental evidence supports these conclusions, at least for high Tc superconductors (Reference 61). For thin films made by sputtering, the quality of the superconducting film seems to depend crucially on the perfection of the substrate surface. This question has been investigated mainly by Benvenuti *et al.* (Reference 51), who showed a correlation between the RRR of the film and the chemical treatment of the underlying Cu substrate. There exist serious indications that very good films can indeed be obtained, since NbTiN samples made at Saclay by reactive sputtering now reach reproducibly residual surface resistances less than 100 nΩ at 4 GHz, with little dependence of this surface resistance versus RF field up to 35 mT (Reference 62).

The thermal nitriding of Nb cavities is also a way which probably deserves investigation. It consists in heating niobium in a nitrogen atmosphere to produce a NbN layer. Recent progress has been made by Benvenuti *et al.* in the mastery of the kinetic aspect of the reaction, as a function of temperature and nitrogen pressure (Reference 63). The improvement in critical temperature is spectacular, but preferential diffusion of nitrogen in the grain boundaries may be expected, and this may affect the residual surface resistance of the NbN film.

The preferred applications of thin film cavities will be focussed on accelerators requiring large duty cycle and small RF dissipation, for which the criterion of high gradient is not a very high priority. Here, thin films open perspectives of simplified cryogenics, since operation of the cavity at high temperatures will be allowed by the very small BCS contribution to the surface resistance.

9 PERSPECTIVES FOR $\beta = 1$ SUPERCONDUCTING CAVITIES

SC cavity technology is now applied to a wide variety of accelerators, taking advantage of the low RF losses in the cavities. This feature can be exploited in different ways, depending on the particular application under consideration: A very complete account of these applications can be found in References 1–9. Table 2 summarizes the accelerator types using $\beta = 1$ SC cavities. We shall only deal here with the most recent trends and results.

The advantages of superconducting cavities for accelerators of high luminosity are well known and well documented (References 1–9). $\beta = 1$ superconducting cavities have been successful in storage rings, and in large duty cycle electron linacs. With the years, these applications are spreading, and becoming more and more convincing. The good news from these last two years is the superb behaviour of the CEBAF cavities. Nearly all cavities tested so far exceed by large amounts the design value (Figure 1).

TABLE 2: Main applications of SC cavities to $\beta = 1$ accelerators

Accelerator type	Required cavity characteristics
Linacs with large duty cycle: – for Nucl. Phys. (CEBAF, Darmstadt, ELFE) – for free electron lasers (LISA, HEPL, JAERI...)	Low RF dissipation
High energy hadron rings (LHC, SSC, RHIC)	
High intensity accelerators: – Storage rings (KEK, HERA, LEP200) – Hadron linacs (ESS, AWT...)	Large diameter iris; Couplers with large power handling capabilities
e^+e^- linear collider (TESLA)	High accelerating gradient

Now, other domains of application are opening, exploiting the advantages of RF superconductivity in other ways:

The idea that RF superconductivity could also be applied to accelerators at the high energy frontier is not new (Reference 64), but is gaining strength. The future high energy e^+e^- collider might use superconducting cavities. The TESLA collaboration (Reference 65), which promotes this idea, has grown considerably during the last two years. Here, the reduced RF dissipation of superconductors is still used to advantage, but the large diameter beam holes permitted by SC cavities (and the machine parameters which derive from this feature) is probably the most convincing argument in favor of the TESLA project. Altogether, TESLA has already emerged as a credible option for an e^+e^- collider in the TeV range. The main challenge of the TESLA cavities will be to reach accelerating gradient of the order of 25 MV/m in 9 cell, 1.3 GHz cavities. The gradients obtained recently in Cornell, Saclay, Wuppertal, CEBAF or KEK suggest that this goal can be reached, but an important amount of R&D will certainly be required to obtain it in a reproducible manner and at low cost.

There is also a new and powerful interest in high intensity hadron linacs, e.g., for spallation sources. The idea that these accelerators could use superconducting cavities is new and exciting (Reference 66). Here again, the large diameter irises of superconducting cavities are exploited, but this time, the main interest seems to be the reduced activation by the beam halo. These accelerators will necessarily operate at rather low frequency, similar to the LEP frequency (350 MHz). For the same reasons than at LEP, thin film cavities (maybe niobium nitride?) could be an interesting option for these accelerators.

RF superconductivity is a reliable technology. Some accelerators like Tristan at KEK have already used it for a long time. No long term degradation of the cavity performance have been observed (Reference 67); the essentials of the physical phenomena underlying the behaviour of SC cavities now seem to be understood at the laboratory level. But RF superconductivity is still far from its theoretical limits. The remaining problems are probably of technological order. There is still ample room for improvement, if the present limitations imposed by cleanliness and preservation of the surface quality can be pushed further.

RF superconductivity has reached a stage of validation at the industrial level. One of the main drawbacks of this technology is its cost. A significant proportion of this cost is the cavity fabrication. An important challenge for the future years will be to cut it down by improved cavity fabrication techniques.

As far as one can see, the main R&D topics which should be addressed to improve cavities could thus be as follows:

(i) field emission, in connection with improved techniques to achieve a good cleanliness of the cavity surface;

(ii) thin films;

(iii) improved fabrication techniques, in connection with the metallurgical aspects of Nb elaboration and purification;

RF superconductivity is already a mature technology, but important improvements can still be expected if R&D activities are continued in close collaboration between the laboratories and industry. For sure, the technical and economical implications of this adventure are exciting!

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