# Status and applications of superconducting cavities

B. Bonin

CEA DAPNIA SEA

Saclay F-91191 Gif sur Yvette, France

**Abstract**

This paper sketches the most recent trends of the R&D and applications of RF superconductivity to accelerators.

## 1. INTRODUCTION

Superconducting cavities have now been used in many accelerators, eg heavy ion linacs, 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 [1-5]. 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 RF couplers and windows has been deliberately omitted in this article. The most important issues of the R&D on superconducting cavities, ie the quest for high gradients and reduced RF dissipation, will be reviewed.

## 2. HIGH GRADIENTS

The accelerating gradients available in accelerating superconducting structures 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 cleanliness standards [6], the development of RF processing techniques like High Peak Power Processing [7-9], the availability of higher purity niobium [10], and the generalization of the heat treatment of the cavities [11,12].

Accelerating gradients are still limited by two phenomena: quenches and field emission. 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 obtained without electron emission on areas of the order of 1 $cm^2$ [13]; superconducting radio-frequency quadrupoles (RFQ) have reached a peak electric field of 128 MV/m [14]; 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 = 2K), [15], (fig. 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. 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 emission, in 9-cell structures at 1.3 GHz. With the ratio $E_{surface}/E_{acc}$ = 2 currently obtained in present day "$\beta$=1" cavity designs, this corresponds to accelerating gradients of 15 MV/m.

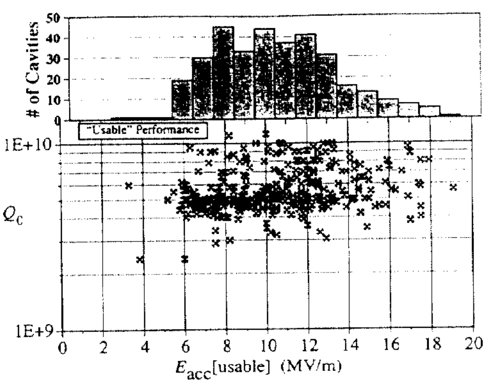


Figure 1 Systematics of the 1.5 GHz, 5-cell cavities from CEBAF (from ref. 15).

### 2.1 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 [16]. Recent systematic studies have confirmed that deliberate contamination of the cavity surface by conducting, micrometer sized particles results in heavy field emission [17]. 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. Among the advanced cleaning techniques presently under investigation, high pressure rinsing seems to be most promising [18,19]. Its idea is to use the mechanical action of a high speed water jet to remove micron sized particles adhering on the surface.

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. Despite its considerable potential of improvement, this problem has received much less systematic attention than the problem of cleanliness during the wet process.

### 2.2 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 [7–9]. 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). 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 [20], 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.

### 2.3 Quenches, and the problem of niobium purity

The limitation of gradients by quenches (ie thermal instabilities of the cavity initiated by heating defects) has been a severe one in the past. Improved fabrication techniques and the use of high purity niobium already restrict the occurrence of quenches to about 20% for Nb single cell accelerating cavities in the GHz range with gradients smaller than 15 MV/m. High temperature vacuum annealing of the cavity gives the possibility of increasing the wall thermal conductivity, and the cavity quench threshold. It is striking to see that in all laboratories, the highest gradients have been obtained with fired cavities. 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 (fig. 2). Unfortunately, the heat treatment has many drawbacks: it is expensive and difficult to integrate in a large scale production process. Moreover, it severely degrades the mechanical properties of the cavities. Despite these shortcomings, heat treatment seems to be an obliged detour on the road to high gradients.

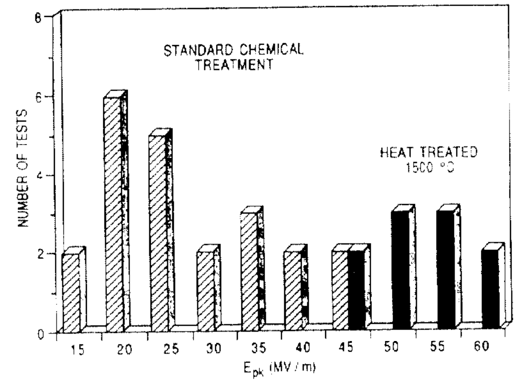


Figure 2 Benefits of the heat treatment on single cell niobium cavities at Cornell (from ref. 1).

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 reach higher gradients after a purification improving their thermal conductivity. Definitely, a niobium purity of RRR 200, which has been the "state of the art" during the last five years, 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 350 with adequate formability can already be ordered from industry. Prospects of further improvement are good, since very high purity Niobium (RRR > 600) is in principle available from russian industry [21]. 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.

## 3. 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 [22] and eradicated to a large extent. In all laboratories, this effort yielded cavities with reproducible residual surface resistance, between 10 and 20 nΩ. Surface resistance as low as a few nΩ have indeed been observed, for example at Wuppertal ([23], fig. 3) or at Saclay. 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 accelerating cavities. This result, obtained thanks to an especially careful magnetic shielding of the cavities, and a minimization of the losses in the cutoff tubes, has considerably clarified the list of possible causes of residual dissipation in superconducting cavities. Putting aside the two major causes already mentioned, this list featured [24] 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 n$\Omega$ 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, the cost of CW accelerators could be reduced by reduction of the needed cryogenic power. This might also permit operation of pulsed accelerators like TESLA with duty cycles larger than the ones envisaged now.

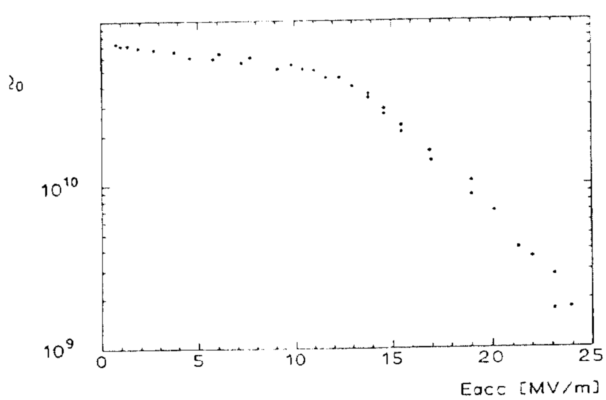


Figure 3 Very high Q-value obtained in a 3 GHz single-cell niobium cavity at Wuppertal (from ref. 23).

## 4. CAVITY FABRICATION

In most cases, low-beta structures are produced in limited number. Their fabrication poses problems which can be solved at the laboratory level. The situation is very different for $\beta$=1 cavities, which are often to be produced in large quantities for a given accelerator project. Here, the fabrication cost and quality of the product become industrial problems.

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 for cavities with a large number of cells. Besides, even with a 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.

Alternative approaches based either on spinning a single niobium sheet [26] or hydroforming a tube [27] to produce seamless cavities are under investigation. The drawability of niobium seems to be sufficient for this purpose, but forming of refractory metals is a very delicate process, especially if high purity material is used. These new methods 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. In case of success, these techniques might result in a very significant reduction of costs for a large scale cavity production.

### 4.1 Thin superconducting films

In RF superconducting structures, 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 (eg 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.

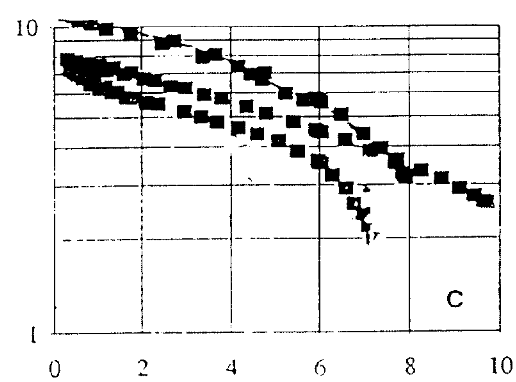


Figure 4 Typical Q ($10^9$) vs $E_{acc}$ (MV/m) of accepted Nb/Cu cavities for LEP, as measured in vertical test cryostat (from ref. 28).

CERN has developed with success the technique of Nb thin film deposition on copper for the LEP200 cavities [28,29]. 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", causing 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. Full scale production of the cavities has now started, and the first assembled cryomodules arrive for qualification at CERN.

Thin film samples of the intermetallic compounds NbN, NbTiN and $Nb_3Sn$ are being elaborated in a few laboratories, e.g CERN, Wuppertal or Saclay [30]. Unfortunately, the residual surface resistance of these films is rather high (a few hundreds of n$\Omega$ at GHz frequencies), and increases with increasing RF field. Moreover, the gradients obtained (of the order of 35 mT) are still too low for most applications. The present limitations of performance are probably curable. They are thought to be due to imperfections in the thin film morphology, causing granular superconductivity [31].

Overall, thin films other than Nb/Cu have promising results on samples, but no convincing high-performance cavity has been fabricated yet using these films. 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.

## 5. PERSPECTIVES FOR 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 (Table 1). We shall only deal here with the most recent trends and results.

Until recently, the only "low beta" application of RF superconductivity has been for heavy ion linacs. The increasing number of such accelerators indicates that this will continue to be a dominant application. The development of new resonator shapes like superconducting radiofrequency quadrupoles and spoke resonators might open the field: new applications such as high intensity CW ion beams or high duty cycle proton beams for neutron spallation sources are forthcoming.

The advantages of superconducting cavities for accelerators of high luminosity are well known and well documented [1-5]. $\beta$ = 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 (fig. 1).

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

Table 1 Main applications of SC accelerating cavities

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 [32], but is gaining strength. The future high energy e+ e- collider might use superconducting cavities. The TESLA collaboration [33], which promotes this idea, has grown considerably during the last two years. Here, the reduced RF dissipation of superconductors is still exploited, 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, eg for spallation sources. The idea that these accelerators could use superconducting cavities [34] is new and exciting. 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 heavy ion linacs or electron rings like Tristan at KEK have already used it for a long time. No long term degradation of the cavity performance have been observed [35]; 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 obstacles to the development of this technology is its cost. An important challenge for the future years will be to cut it down.

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 superconducting films;

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

**Acknowledgements.**

The author wishes to thank his colleagues from CEBAF, CERN, Cornell, DESY, KEK, Wuppertal, Los Alamos for kindly supplying information for this review.

## 6. REFERENCES

1. H. Padamsee, K.W. Shepard and R. Sundelin, Ann. Rev. Nucl. Part. Sci. 43 (1993) 635

2. P. Kneisel, J. Vac. Sci. Technol. A11 (1993) 1575

3. W. Weingarten, Particle World 1 (1990) 93

4. D. Proch, Proc of the 1993 Particle Accelerator Conference, Washington (1993) 758

5. H. F Dylla, L. R. Doolittle and J. F. Benesch, Proc of the 1993 Particle Accelerator Conference, Washington (1993) 748

6. C. Z. Antoine et al. Proc. V$^{th}$ Workshop on RF Superconductivity, D. Proch, ed., Hamburg (1991) 456

7. J. Kirchgessner et al., Proc of the 1989 Particle Accelerator Conference, Chicago (1989) 482

8. J. Graber, PhD Thesis, Cornell University, Ithaca (1993)

9. H. Padamsee et al., Proc. V$^{th}$ Workshop on RF Superconductivity, D. Proch, ed., Hamburg (1991) 37

10. M. Hörmann, J. Less Common Metals 139 (1988) 1

11. Q. S. Shu et al., NIM A 278 (1989) 329

12. P. Kneisel, J. Less Comm. Metals 139 (1988) 173

13. D. Moffat et al. Cornell report CLNS 89934, Cornell University, Ithaca, NY (1989)

14. J. Delayen and K.W. Shepard, Appl. Phys. Lett. 57 (1990) 514

15. C. Reece et al. Proc of the 1993 Particle Accelerator Conference, Washington (1993) 1016

16. P. Niedermann, "Experiments on enhanced Field Emission", PhD dissertation, Université de Genève (1986)

17. M. Jimenez et al., J. Phys. D: Appl. Phys. 26 (1993) 1503

18. P. Bernard, D. Bloess et al., Proc. of the III$^{rd}$ European Particle Accelerator Conference, Berlin (1992) 1269

19. B. Rusnak et al. Proc. of the 1992 Lin. Acc. Conf., Ottawa, C. R. Hoffmann, ed. (1992) 728

20. I. Campisi, IEEE Trans. Mag. 21 (1985) 134

21. A. V. Eliutin et al., Proc. V$^{th}$ Workshop on RF Superconductivity, D. Proch, ed., Hamburg (1991) 426

22. B. Bonin and R. Röth, Part. Accelerators, 50 (1992) 59

23. D. Reschke, private communication

24. J. M. Pierce et al. Proc. IX$^{th}$ Int. Conf. Low Temp. Phys. (Plenum press, NY (1965) 396

25. J. Kirchgessner, Proc of the IIIrd Workshop on RF superconductivity (Argonne Ntl Lab. 1988) Report ANL. Phys. 88–1 (1988) p 533

26. V. Palmieri et al., contribution to this conference, and article to be published in NIM (1994)

27. C. Hauviller, private communication.

28. G. Cavallari et al., Proc of the 1993 Particle Accelerator Conference, Washington (1993) 806 and refs. therein.

29. C. Benvenuti et al. XX Int. Conf. on Low Temp. Phys., Eugene, Oregon, USA (1993)

30. P. Bosland et al., Proc. of the Third European Particle Accelerator Conference, Berlin (1992) 1316

31. B. Bonin, H. Safa, Supercond. Sci. Technol. 4 (1991) 257

32. M. Tigner, Nuovo Cimento 37 (1965) 1228

33. H. Padamsee, editor. Proc. of the 1$^{st}$ TESLA Workshop, CLNS report 90–1029 (1990)

34. H. Lengeler, VI$^{th}$ Workshop on RF Superconductivity, ed . R. Sundelin, CEBAF (1993)

35. K. Kubo et al. Proc. XV$^{th}$ Int. Conf. on High Energy Accelerators HEACC 92, ed. J. Rossbach, Hamburg (1992) 691