

## REVIEW OF PROGRESS IN SUPERCONDUCTING HIGH-BETA STRUCTURES\*

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### Abstract

During the past two years, there has been substantial progress in superconducting high-beta cavities in a number of areas. Understanding of the "Q-disease," which occurs when a cavity is held for prolonged periods near 100K, has advanced, and techniques for mitigating this problem have improved. Progress has been made in the use of high peak power processing to suppress field emission. Cell geometries have improved to reduce the ratio of peak surface electric field to accelerating field, and trapped mode behavior has been found to permit use of nine cells for some applications. The operating experience base for cavities installed in accelerators has increased substantially, as has the performance experience base for industrially manufactured cavities, including both solid niobium and sputter-coated copper. Additional applications for superconducting cavities have been identified. Progress has been made toward the design and construction of a Tera-Electron-Volt Superconducting Linear Accelerator (TESLA) test bed.

### Introduction

This paper discusses improvements which have been made in the science of RF superconductivity during the last two years, the present status of major high-beta applications, and applications which are planned or under consideration for the future.

### Improvements in Cavity Q's

The "Q-disease" is a degradation of the cavity  $Q_0$  which occurs when the cavity is held near 100K for the order of an hour or more before cooling down to superconducting temperatures. The size of the degradation can be several orders of magnitude. Recent measurements [1] have shown the dangerous range to be 70K to 150K, and the process to be reversible upon warming to a temperature above 200K. The same measurements also determined the degree of degradation as a function of holding time at the intermediate temperature.

The "Q-disease" was first observed relatively recently at Darmstadt and DESY. The cavities in which it was observed were made of high residual resistivity ratio

(RRR) Nb, rather than the previously used reactor grade Nb. The high RRR Nb is used to improve the thermal conductivity at low temperatures, and stabilize the structure against thermal runaway caused by localized heat sources. It is believed that niobium hydride precipitation [2] is responsible for the "Q-disease," that both high residual resistivity ratio (RRR) Nb and reactor grade Nb contain hydrogen, but the higher oxygen concentration in the reactor grade Nb "pins" the hydrogen so that it cannot precipitate. A test cavity was recently made of reactor grade Nb to confirm that the type of Nb, and not some other change in procedures, was responsible for the change in Q behavior; the "Q-disease" was absent in this test cavity [1].

Anodization of the Nb surface is also found [1] to reduce the effect of the "Q-disease." Furnace outgassing at 760°C for 5 - 10 hours [3] is found to eliminate the "Q-disease;" since only hydrogen is appreciably outgassed at this temperature, it further supports the hydride theory.

At present, there are three practical methods to keep the effects of the "Q-disease" at acceptable levels: (1) cool the cavity rapidly (>50K/hour) through the dangerous temperature region, (2) degas the cavity at 760°C, and (3) anodize the cavity surface.

Another area in which there is improved understanding is that of the question of why sputter coated niobium cavities are highly insensitive to the presence of DC magnetic fields at the time of cool-down. This has recently been explained at CERN [4] as being due to a much smaller coherence length in sputtered Nb than is found in bulk Nb. The lower coherence length reduces the area of each flux quantum vortex, which in turn reduces the normal conducting surface area seen by the RF currents.

### Improvements in Cavity Gradients

One procedure which has been shown to produce CW gradients which are approximately 50% higher than those otherwise achieved is high peak power processing [5]. The principle by which this technique operates is that the cavity is filled with RF energy faster than any breakdown zones that are initiated can propagate. The field emission current density is sufficiently high that it will melt or vaporize the field emission site, if the local electric field is high enough to produce the requisite field emission current. If one attempted to fill the cavity

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slowly, a breakdown zone would propagate to a sufficiently large area that the cavity RF energy would be dissipated by this normal conducting area, thereby preventing the electric field from reaching a high enough value to produce adequate field emission to destroy the emitter. A typical filling time for a cavity during high peak power processing is 0.5 ms, whereas the time required to decrease the  $Q_0$  of a cavity to 100,000 due to quench zone propagation is of the order of 100 ms. The requisites for high peak power processing are a source of adequate peak power, and an input coupling network which can handle this peak power and which provides adequate matching for both the high peak power processing and for normal operation. A suitable input coupling network will also permit a cavity to be reprocessed in situ.

Typical  $Q_0$  vs. gradient curves, with and without high peak power processing, are shown in Figure 1. In addition to providing a useful result, the work at Cornell has yielded a number of interesting phenomena which may lead to further understanding of the processes involved. One phenomenon is the formation of craters at the processing site. The existence of craters, rather than smooth melted zones, suggests that the vapor pressure or Lorentz forces are significant compared to the surface tension of the molten niobium. This has the undesirable aspect that the craters yield a geometrical enhancement of the field, which will limit the ultimate potential of the technique. Another interesting phenomenon is that of starbursts. The starburst patterns have been identified as areas where the normally present oxide layers on the surface have been removed. The removal process may be related to plasma etching during a local arc. A similar phenomenon is that of tracking; in this case, a pattern of what appear to be cracks in the oxide layer appear. These "cracks" frequently change direction abruptly. They could conceivably be caused by severe thermal expansion. Another curious phenomenon is that of ripples. The ripples look somewhat like (but are not) fingerprints. Their period is of the same order of magnitude as the distance a plasma front would advance in half an RF period, so it is conceivable that the phenomenon is caused by the intersection of RF currents on a plasma front with matching currents on the metal surface.

The work at Cornell has also demonstrated that the cavity surfaces are not as free of foreign materials as one would hope. Iron, chromium, nickel, copper, titanium, indium, and Teflon have been found at some, but not all, processing sites. Whether these materials were present in the bulk niobium, or if they got onto the surface during cavity manufacture, cavity processing, or subsequent handling is unknown but is a very important question.

The Cornell studies have also examined the distribution of processing sites in S-band cavities. They are found predominantly in the highest electric field region,

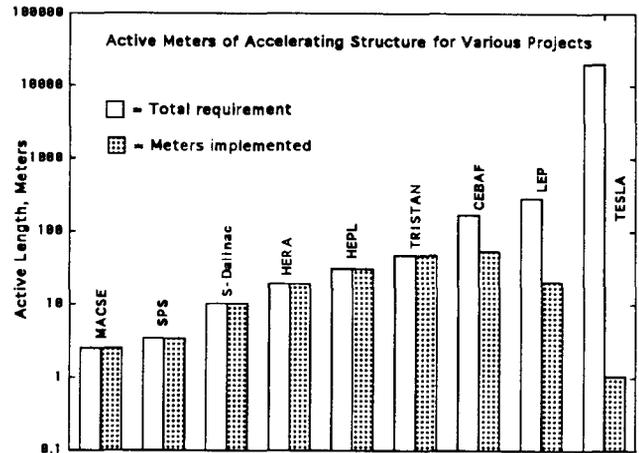


Fig. 1 Active meters of accelerating structure for various projects.

and a substantial number are also found in the region where both the electric and magnetic fields are relatively high.

In recent tests on a 2-cell S-band cavity, a peak electric field of 57 MV/m was reached. After high power processing, peak electric fields of 85 and 100 MV/m were obtained in two tests [6].

Other work has also yielded improvements in obtaining consistently good performance. Very careful surface preparation at CEBAF [7] has yielded peak surface electric fields on three different 1-cell, 1500 MHz cavities in excess of 51 MV/m using buffered chemical polishing (BCP) as the principal surface treatment. By a similar process, but one in which the cavity was not exposed to other than clean room air following chemical processing, accelerating gradients grouped around 21 MV/m have been obtained in 1-cell, 1500 MHz cavities at Saclay [8]. Multiple tests at Los Alamos have shown that the gradients achieved if cavities are pre-soaked in nitric acid are 50% higher than if they are not, where the final step in both cases is buffered chemical processing [9].

For copper cavities sputter coated with Nb, CERN [10] has found that high pressure water rinsing, followed by pure ethanol rinsing to avoid water stains, is of major benefit in suppressing field emission in those cavities.

Tests by Los Alamos [11], and Saclay and IBM [12], in which clean silicon wafers were subjected to the same chemistry as superconducting cavities, determined that the more cavity processing steps and the longer the duration of those steps, the greater the number of residual particles per unit area on the silicon. This indicates significant room for improvement in the cavity processing techniques.

CEBAF [13], has reconfirmed an observation which has been made at many laboratories, namely that the pattern in which cavity systems are cooled down affects the performance of the cavities. It was observed that the lower cavity in cavity pair tests systematically showed

worse field emission than the upper cavity. By placing a shroud around the lower cavity so that the beam pipes were the first region to cool, the gradients in the lower cavity increased to become equal those of the upper cavities. Since the amount of residual gas in the system at the time of cool-down corresponds to around  $10^{-4}$  monolayers, and since the manner in which the cavity is BCP processed guarantees that it has of the order of magnitude of one monolayer on it to start with, the effect of cool-down patterns is quite peculiar. Two hypotheses are 1) the residual gas condenses in very localized spots or 2) the surface mobility of the already-adsorbed gases is sufficiently high that they can migrate to the cold regions during the cool-down process.

### Improvements in Cavity Designs

In order to decrease the ratio of  $E_p/E_{acc}$ , iris diameters have been reduced in some recent designs, and the iris shape has been further optimized. This has reduced  $E_p/E_{acc}$  from  $\sim 2.5$  to  $\sim 2.0$ . Since field emission is the dominant gradient limitation, this change should be of significant benefit.

For isochronous accelerators in which only transverse higher order modes (HOM's) are a significant concern, combinations of iris diameters, iris shapes, and equatorial shapes have been modified to minimize the trapping of HOM's (trapping refers to the absence of significant amplitudes in cells to which the damping is applied). Custom tuning of end cells to tilt HOM patterns toward the cell to be used for damping has been found to be of significant benefit [14]. These procedures yield  $Q_{ext}$  values of the order of  $10^5$  for important HOM's in 9-cell cavities. These Q values are acceptable to prevent cumulative wakefield problems in the TESLA linear collider design. Maximizing the number of cells per cavity structure is an important objective because it minimizes system costs.

Problems which merit further exploration are the effect of mechanical tolerances on the trapping of mode patterns, and methods of dealing with the detuning of the structure caused by Lorentz forces when the cavity is operated in a pulsed mode, as it is in TESLA.

### Expansion of the Operating Data Base for Superconducting Cavity Installations

During the past two years, the number of superconducting cavity operating hours in large installations has increased substantially.

TRISTAN [15] has been operating with 47.2 active meters of superconducting cavities installed since 1988. The cavities are 508 MHz, 5-cell units, with two cavities per cryostat. Over 10,000 hours of physics running using these cavities have been logged. The average

breakdown gradient is  $\sim 6.6$  MV/m, and the average  $Q_0$  value is  $\sim 2 \cdot 10^9$ . On average, there has been no significant degradation of either of these parameters since installation. During physics running, the cavities are operated between 3.3 and 4.7 MV/m. Whereas there have been no problems with the basic cavities, several of the peripheral devices have been or are being upgraded to eliminate problems. The size of HOM feedthroughs was increased to eliminate overheating. Input window cooling channel water corrosion has been a problem. Arc detectors were added to the window to turn off the RF in the event of an arc. Piezo tuner retention bolts had to be shielded to control radiation damage. Modifications to the indium seal compression methods are needed to maintain spring loading in the presence of repeated thermal cycles. One phenomenon which is not yet fully understood is the occurrence of fast quenches (of the order of microseconds, not tens of milliseconds) in the presence of beam currents around 12 mA. It is suspected that either scattered synchrotron radiation or lost beam particles are responsible, and that the mechanism involves a gas discharge, but the subject is under active investigation.

MACSE [16] is operating five five-cell, 1500 MHz cavities, for a total of 2.5 meters. The average breakdown field is 6.5 MV/m at a  $Q_0$  of  $\sim 0.6 \cdot 10^9$  (reciprocally averaged). The relatively low  $Q_0$  value is the result of a cold sapphire window failure, which contaminated one of the cavities. The operating beam current is 100  $\mu$ A. One particularly significant aspect of this system is that four cavities are fed from a single klystron, and the vector sum of the cavity amplitudes is formed with sufficient accuracy that the  $20^\circ$  microphonic amplitude in each cavity is reduced by the control system to  $\leq 0.1^\circ$  as seen by the beam.

LEP [17] installed 20.4 active meters of cavities in 1989. The system consists of cryostats each containing four four-cell, 352 MHz cavities. Due to various non-fundamental limitations, these cavities are operated with beam at  $\leq 3.7$  MV/m. An additional 26.9 meters of cavity made of sheet niobium have been tested in the lab. These cavities have an average breakdown gradient of 7.2 MV/m, and have an average  $Q_0$  of  $3.6 \cdot 10^9$  at 5 MV/m. Sputter coated cavities, which are being made by three companies for CERN, are starting to meet their specification of  $Q_0 \geq 4 \cdot 10^9$  at 6 MV/m. As previously mentioned, CERN has discovered that high pressure water rinsing followed by ethanol rinsing is a significant help in controlling field emission. The total SC cavity installation required for the LEP II conversion is 286.16 m, which will make LEP the largest installation presently under construction.

HERA [18] has had 19.2 active meters of cavity installed in the HERA  $e^-$  ring since May 1991. This

system operates with 4 mA of beam at 3.6 MV/m. The maximum gradient is 4 MV/m, and  $Q_0 = 1.1 \cdot 10^9$  at 3.3 MV/m. The gradient is limited by refrigerator power, which in turn is limited by the "Q-disease." The cavities are 4-cell, 500 MHz structures, installed 2 to a cryostat.

S-Dalinac [19] has 10.2 active meters installed, and achieved first beam in December 1990. The beam current is 20  $\mu$ A and the operating gradient is 5.9 MV/m. The cavities are primarily 20-cell, 3 GHz structures.

HEPL [20] installed ~30.8 active meters of structure, and has been operating since 1974. The accelerating gradient is ~3 MV/m at a  $Q_0$  of  $3 \cdot 10^9$ . The gradient is limited by one-sided multipacting at the equator, which is intrinsic to the cell shape chosen before this phenomenon was discovered.

CEBAF [21] had 53.0 active meters of structure installed as of July 24, and is installing cavities at the rate of 8.0 meters per month. The ultimate length to be installed is 169.22 meters, although there is room for 209.27 meters. The cavities are 5-cell, 1497 MHz structures, and are installed 8 to a cryostat. 18 cavities have been operated with up to 367  $\mu$ A of beam since June 1991, some of the time with one local recirculation (up to 190  $\mu$ A per pass). These cavities are operated at a gradient of 5 MV/m (they can be operated with beam at higher gradients), and have exhibited no systematic degradation in gradient or  $Q$ . The average usable gradient (defined as the lowest of: a gradient where 1.3 watts of field emission is encountered, a gradient 10% below the breakdown field, and a gradient at which the  $Q_0$  drops below the specification of  $2.4 \cdot 10^9$ ) in vertical cavity pair tests is 8.8 MV/m, and the average  $Q_0$  at that gradient  $5.4 \cdot 10^9$ . The average usable gradient in tunnel commissioning is 7.6 MV/m, and the average  $Q_0$  is substantially equal to that in the vertical tests. The lower gradient observed in the tunnel is, in part, due to the fact that the klystron output power is insufficient to drive the cavities above ~10 MV/m. The cavities are continuously kept under vacuum after they are first assembled as pairs.

### Expanded Applications for Superconducting Cavities

A number of new or expanded applications for superconducting cavities are at various stages of development.

SC cavities as FEL drivers were first used at Stanford, and are in the process of being implemented at Darmstadt and Frascati. FEL applications are under consideration at BNL, LBL, and CEBAF, among others.

A 402.5 MHz 1-cell SC cavity has been implemented as a "scruncher" at Los Alamos, where it is used to rotate the longitudinal phase space of the beam [22].

A pion post-accelerator, PILAC, is under consideration at Los Alamos [23]. SC cavities have the advantage of providing high gradient at high duty cycle, so that decay of the pions in flight is not excessive.

SC cavities have been developed for use in B-Factories [24]. They have the advantage of providing minimal impedance to the beam (due to a small number of cells and a large beam hole). Related cavities are being developed for "crabbing," a process of rotating bunches so that they collide head-on even though the beams cross at an angle.

SC cavities would be useful in muon colliders, if such a device proves to be feasible, since rapid acceleration of the muons would be essential to minimize the fraction which decay before reaching full energy.

In very large circumference hadron colliders, SC cavities have the advantage of presenting low R/Q, which minimizes the driving term for longitudinal instabilities associated with revolution harmonics and their sidebands.

Use of SC cavities for waste transmutation facilities has the advantage of maximizing wall plug efficiency, which is an overall objective of a nuclear power cycle.

Use of pulsed SC cavities for linear colliders has the advantage that the high  $Q_0$  reduces the peak power needed to fill the cavities [25]. The slow filling of the cavity, and correspondingly long RF pulse, permit bunches to be passed through the cavity at widely spaced intervals (1 km). The wide bunch spacing has three benefits: there is ample time between bunch passages to damp the wakes from the preceding bunch, low repetition rate pulsing permits low frequencies to be used without dumping unreasonable quantities of stored RF energy (which, in turn, has the advantage that the single-bunch head-tail wakefields are greatly reduced), and the stored energy contained in the beam within the linac at any instant in time is minimized. The low frequency and high duty cycle permit good luminosities to be achieved by the use of large numbers of bunches of relatively high charge; this, in turn, has the substantial benefit that the allowed height of the bunch at the interaction point is much larger than with other approaches. The tolerances on alignment and vibration along the linac are greatly reduced, and no BNS damping is required.

The DESY scientific advisory council has recommended that DESY proceed with the construction of a TESLA (TeV Superconducting Linear Accelerator) test bed as a very high priority activity. DESY is proceeding with this activity, and has been joined by collaborators from at least CERN, Cornell University, Fermilab, INFN, Saclay, and the University of Wuppertal.

### Summary

Methods for improving both gradient and  $Q_0$  performance have continued to advance. Experience with large scale applications has been favorable, although actual operating gradients are low in several cases. Proposed future applications for superconducting radio frequency cavities offer substantial benefits.

### References

- [1] P. Kneisel and K. Saito, "Superconducting Niobium Cavities with High Gradients," this conference.
- [2] R. Röth et al., Proceedings of the Second European Particle Accelerator Conference, Nice, 303 (1990).
- [3] E. Kako et al., "Development of High Gradient L-Band Superconducting Cavities," 1992 High Energy Accelerator Conference, Hamburg.
- [4] Ph. Bernard et al., "Superconducting Niobium Sputter-Coated Copper Cavities at 1500 MHz," 1992 European Particle Accelerator Conference, Berlin.
- [5] H. Padamsee, "Recent Status of Superconducting Accelerator Cavities," 1992 ICFA Workshop on AC Superconductivity, Tsukuba.
- [6] H. Padamsee, private communication.
- [7] Ibid., Ref. 1.
- [8] A. Mosnier, private communication.
- [9] J. DiMarco, private communication.
- [10] Ibid., Ref. 4.
- [11] R. Rusnak et al., "Evaluation of Surface Contamination and Cleaning Techniques on Superconducting RF Cavities," this conference.
- [12] A. Mosnier, presentation at the Linear Collider 1992 Workshop, Garmisch-Partenkirchen.
- [13] C. Reece and J. Susta, private communication.
- [14] J. Secutowicz, presentation at the Linear Collider 1992 Workshop, Garmisch-Partenkirchen.
- [15] K. Kubo et al., "Four Years of Operation of the Tristan Superconducting RF System," 1992 High Energy Accelerator Conference, Hamburg; S. Noguchi, private communication.
- [16] A. Mosnier, private communication.
- [17] C. Wyss, "Status of the LEP Energy Upgrade," 1992 European Particle Accelerator Conference, Berlin.
- [18] D. Proch, private communication.
- [19] H. Genz et al., "Operational Experience and Results from the S-DALINAC," 1992 European Particle Accelerator Conference, Berlin.
- [20] Proceedings of the 1974 High Energy Accelerator Conference, Stanford.
- [21] C. Reece et al., "Performance and Installation Status of Superconducting Cavities at CEBAF," 1992 High Energy Accelerator Conference, Hamburg.
- [22] J. O'Donnell, private communication; to be published in Nuclear Instruments and Methods.
- [23] G. Swain, "Linac Reference Design for PILAC," PILAC Technical Note No. 14, Los Alamos National Laboratory LA-UR-91-717 (1991).
- [24] "CESR-B Conceptual Design for a B Factory Based on CESR," Cornell University CLNS 91-1050 (1991).
- [25] "2 TeV CM e+e- Linear Collider," Cornell University CLNS-85/709 (1985); "High Gradient Superconducting RF," Proceedings of the 1987 IEEE Particle Accelerator Conference, Washington, DC, p. 68-72 (1987).