SUPERCONDUCTING RF R&D TOWARD HIGH GRADIENT*

C.M. Ginsburg[#], Fermilab, Batavia, IL 60510, U.S.A.

Abstract

High-beta superconducting RF elliptical cavities are being developed in large numbers for several accelerator projects including the International Linear Collider (ILC). In recent years, the understanding of cavity performance limitations has improved significantly, leading to better than 40 MV/m in some cavities. However, further improvement is needed to reach reliably the 31.5 MV/m operating gradient proposed for the ILC Main Linac cavities. World-wide R&D on the cavity gradient frontier includes improved surface cleaning and smoothing treatments, development of alternative cavity shapes and materials, and novel cavity manufacturing techniques. Substantial progress has been made with diagnostic instrumentation to understand cavity performance limitations. Some highlights of the efforts in superconducting RF R&D toward achieving higher gradients in high-beta elliptical cavities are reviewed.

INTRODUCTION

High-gradient superconducting radiofrequency (SRF) cavity technology is being advanced on many fronts because many cavities are needed for current and proposed projects: (1) the test/user facilities STF (KEK), NML (Fermilab), and FLASH (DESY), (2) the European XFEL currently under construction, (3) Project X at Fermilab, and (4) the International Linear Collider (ILC). The common requirements or choices for the high-gradient cavities in these projects are gradients of at least 23 MV/m, beta=1, elliptical shape and an accelerating mode frequency of 1.3 GHz. Recent studies intended to improve gradients in these cavities are reviewed.

First, the requirements for achieving high gradient and current standard cavity treatments are described. Second, some highlights of studies are shown: surface treatments to reduce field emission, alternative shapes to improve average performance, and new fabrication techniques and materials to reduce cost or improve performance. Third, one fundamental study into the cause of poor cavity quality factor (Q_0) at high gradients is shown. Finally, the cavity diagnostic instrumentation which has been used and/or developed within the last year to study cavity performance and sources of premature quenches is described.

ACHIEVING HIGH GRADIENT

Because RF fields occupy the first ~40 nm of the inner cavity surface for these cavities, the quality of the innermost surface is critical and must be carefully controlled. For the niobium sheets which are used to make cavities, RRR of at least 300 is specified for the ILC[1]. Eddy current scanning (ECS) of all sheets is now done before cavity fabrication. ECS has proven to be a very useful technique to provide feedback to material vendors which has resulted in an overall improvement in the delivered material in recent years. The cavity inner surface has to be very smooth, with no inclusions of foreign particles, or topological defects such as bumps or pits or sharp grain boundaries. No dust or other microscopic contaminants may be introduced after the final surface preparation which could contribute to field emission.

Cavity cell shapes have been optimized for low peak surface magnetic field (H_{peak}) and low peak surface electric field (E_{peak}) relative to the gradient (E_{acc}), as well as ease of surface processing and fabrication.

Many cavities have reached 35 MV/m or more in the last decade, particularly single-cell cavities of varying elliptical shapes and 9-cell Tesla-shape cavities [2].

SURFACE PROCESSING

The surface treatment intended to maximize cavity performance which was developed for the ILC [3] includes initial preparation steps to remove ~150 μm from the inner surface using electropolishing (EP). This initial removal step is also done with centrifugal barrel polishing (CBP) or buffered chemical polishing (BCP) at some labs, though the maximum gradients reached with BCP as the initial preparation step are lower than those achieved using the other methods. Cavities then undergo an 800°C annealing step, to drive hydrogen from the surface. The final preparation steps include degreasing with detergent, another light electropolishing (~20 μm), a high pressure rinse (HPR) with ultrapure water, drying in a class-10 cleanroom, and then evacuation and low-temperature baking (120°C) for about 48 hours after the final assembly with couplers. Additional treatments after the final EP are being studied to reduce field emission, and will be described later.

The primary methods for material removal during surface preparation are CBP, EP and BCP. CBP is a standard technique developed for cavities at KEK in which abrasive small stones are placed into a cavity with water to form a slurry and the cavity is rotated. As a centrifugal process, the material is preferentially removed from the equator region. Since standard cavities have an equator weld, CBP is very effective in smoothing the weld. EP is an electrolytic current-supported material removal, and has been developed for use on cavities by KEK in collaboration with industrial partners and adopted

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[#]ginsburg@fnal.gov

at most labs. In this case, the niobium cavity is the anode, and an aluminum cathode is inserted on the cavity axis. The electrolyte is HF(40%):H_2SO_4 in a ratio of 1:9 by volume. Some sulfur remains on the surface after EP and will cause field emission unless it is removed. The EP process is complementary to CBP because the material removal is preferentially on the iris. BCP is performed by filling a cavity with a combination of HF(40%): HNO_3 (65%):H_3PO_4(85%) in a 1:1:2 ratio by volume. BCP is known to cause hydrogen contamination at the surface; this problem can be mitigated by using the appropriate proportion of acid and buffer and by keeping the temperature below about 15°C. BCP is rather less expensive than EP and is often sufficient to produce cavities attaining gradients as high as about 25 MV/m. However, it tends to enhance grain boundaries which may degrade the performance of standard fine-grain cavities. A statistical improvement of maximum gradient was seen after the previous BCP standard was replaced with EP.

Although it is possible now to achieve gradients in 9-cell cavities higher than 35 MV/m, there are several factors which limit cavity performance.

REDUCING FIELD EMISSION

Four field emission studies are described, which aim to improve cavity performance by reducing field emission: flash EP (also known as fresh EP), dry ice cleaning, degreasing, and ethanol rinsing.

In tests at KEK using six single-cell Ichiro-shape cavities, a 3 μm EP using fresh acid after the final EP was studied [4]. A gradient improvement to both average and rms was observed. Furthermore, the treatment was found to increase the gradient at which field emission turns on.

Dry ice cleaning is a less developed but promising alternative being developed at DESY [5]. It reduces or eliminates contaminating particles in several ways: they become brittle upon rapid cooling, they encounter pressure and shearing forces as CO_2 crystals hit the surface, and they are rinsed due to the 500 times increased volume after sublimation. Also, LCO_2 is a good solvent and detergent for hydrocarbons and silicones, etc. Dry ice cleaning is a dry process which leaves no residues, because the loosened contaminants are blown out the ends of the cavities by the positive pressure, and can be performed in a horizontal orientation. Dry ice cavity cleaning might be possible after coupler installation, a procedure likely to introduce field emission. Improved field emission characteristics have been seen in single-cell cavity tests, and an extension of the system to 9-cell cavities is planned.

One of several degreasing R&D studies is that of a KEK 9-cell Ichiro-shape cavity which was processed and tested at KEK and JLab [6]. In an initial test at JLab, the cavity produced substantial field emission which was observed at gradients above 15 MV/m. After the cavity was ultrasonically cleaned with a 2% Micro-90 solution and standard HPR, the field emission was substantially reduced or even eliminated.

An extensive study of ethanol rinsing after the final EP was carried out at DESY [7]. Out of 33 cavities used in the study, 20 were treated using the standard procedure and 13 with an additional ethanol rinse after the final EP. The number of tests in which field emission was observed was substantially reduced. In addition, the maximum gradient was somewhat improved. Since field emission was found to be reduced so substantially, the ethanol rinse is now part of the standard DESY cavity treatment.

FUNDAMENTAL SRF STUDIES

Out of a rich field of fundamental SRF studies, one recent advancement regarding trapped vortices [8] is reported, which addresses the phenomenon of Q-drop, in which the cavity Q_0 drops precipitously at high gradients without field emission.

One hypothesis for Q-drop is trapped vortices, i.e., magnetic flux becoming trapped at surface defects or grain boundaries. The trapped vortices may cause excess power dissipation which can be observed as localized hot spots in a temperature map of the cavity external surface. An experiment performed at JLab involved gluing heaters to the outer cavity surface where a hot spot had previously been observed, and studying the temperature map before and after heating. After the application of a thermal gradient, the hot spot temperature was significantly reduced, and heating was redistributed more evenly over the cavity surface. Because a surface defect could not move, and trapped vortices would be subjected to a force from a temperature gradient, this study supports the hypothesis that trapped vortices may be one component of the heating, and therefore the Q-drop. An improved understanding of the Q-drop phenomenon may lead to reduced power consumption by the cavities.

FUNDAMENTAL CAVITY STRUCTURE

The vast majority of cavities which have been processed and tested in the last decade are Tesla-shape fine-grain cavities [9]. Some fundamental changes to the standard Tesla-shape fine-grain cavities which have been under investigation include changes to the cavity shape, fabrication techniques, and material composition.

Alternative Cavity Shapes

Cell accelerating length and equator diameter are fixed by beta and frequency respectively. However, the details of the shape may be optimized for low field emission (low E_{peak}/E_{acc}) and reduced sensitivity to the fundamental maximum surface magnetic field (low H_{peak}/E_{acc}); see, e.g., ref. [10].

Excellent results on single-cell elliptical cavities have recently been obtained. A re-entrant shape cavity built and tested by Cornell University recently reached 59 MV/m [11], setting a world record for the type of cavities described in this paper. Excellent results have also been achieved with an Ichiro shape cavity at KEK, with a record of 53.5 MV/m [2]. Furthermore, 46.7 ±1.9 MV/m was reached on six single-cell cavities with optimized surface treatment parameters [4]. Another low-loss shape single-cell cavity which was processed and tested by a DESY/KEK collaboration reached 47.3 MV/m [12].

It is rather more difficult to manufacture an excellent multi-cell cavity than an excellent single-cell cavity, and the very high gradients seen in single-cell alternative-shape cavities have not been achieved in 9-cell versions yet. One 9-cell Ichiro-shape cavity, without endgroups, which was processed and tested by a KEK/JLab collaboration reached up to 36 MV/m [13].

The conceptual design for a new cavity shape which simultaneously optimizes both E_{peak}/E_{acc} and H_{peak}/E_{acc} has been proposed [14].

Large-Grain and Single-Grain Niobium

Material is wasted, and a lot of time is required, to roll sheets and stamp out the disks from which fine-grain cavities are made. In principle, it should be possible to save manufacturing costs by slicing an ingot directly into large-grain sheets. It may also be possible to achieve high gradients using BCP only, since the performance of large-grain cavities should be less sensitive to the grain boundary enhancement seen in fine-grain cavities, as long as the grain boundaries are strategically located in a low surface-field regions.

At a recent workshop [15], several issues associated with having large grains at the equator were discussed, such as ragged equator edges, material thinning or ripping at the equator, springback deforming half cells, etc. However, the companies involved in the fabrication work consider these problems surmountable. Effective large-grain ingot cutting methods are being pursued in industry.

Recent experience at DESY with large-grain cavities shows their performance is comparable to fine-grain cavities. It is still unclear whether BCP will be sufficient or whether EP will be necessary. Many 1-cell tests have shown high gradients, in a range comparable to fine-grain cavities. Recent tests on three 9-cell large-grain cavities [16] showed gradients of up to 30 MV/m with BCP only. Further processing with EP degraded the performance of two cavities, one because of field emission and one for an unknown reason, while the performance of the third was substantially improved to 37 MV/m.

Single-crystal niobium cavities have been difficult to produce, because it is difficult to produce large diameter single-grain ingots. Six single-cell single-grain cavities of varying shape and fabrication technique were fabricated, processed and tested recently by a JLab/DESY collaboration [17], with performance found to be comparable to that of fine-grain cavities. Unless substantial performance improvement is seen, the difficulty of producing the cavities may not justify the effort required.

In both the large-grain and single-grain cases, further study of crystal orientation effects is needed.

Hydroformed Niobium

Because electron-beam welding is a substantial portion of the cavity fabrication cost, and may be a source of surface defects which cause premature quenches (described later), reducing the number of equator welds required in cavity fabrication would be advantageous.

Recently, a 9-cell cavity was fabricated using a hydroforming technique [18]. The cavity was built from three 3-cell hydroformed units, so it had only two iris welds and two beampipe welds. The surface was treated with the standard procedure including ethanol rinse. The cavity achieved 30.3 MV/m and was limited by quench without field emission. Because the Q_0 was poor at high gradient, the cavity will be baked at 120°C, which is likely to improve the performance in the next test.

Composite Niobium Material

It may be possible to increase the RF breakdown magnetic field of superconducting cavities by creating a multilayer coating of alternating insulating layers and thin superconducting layers [19]. By using multilayers thinner than the RF penetration depth, the critical magnetic field can be increased from niobium Hc to one similar to high-Tc superconductors, thereby significantly improving the maximum gradient achievable.

Recently, a cavity was prepared with such a composite surface and tested [20]. A 10 nm layer of Al_2O_3 was chemically bonded to the niobium surface of an existing single-cell cavity using atomic layer deposition. The surface was then covered by a 3 nm layer of Nb_2O_5. The cavity was high pressure rinsed and tested, achieving 33 MV/m without Q-drop, restoring it to its best performance. A lack of Q-drop indicates good surface magnetic properties in these promising early results.

UNDERSTANDING CAVITY BEHAVIOR

Quenches and field emission appear as hot spots on the outer cavity surface. Temperature mapping (T-map) systems have been used at nearly all of the labs active in this field for many years to study these phenomena [21]. The existing T-map systems primarily use Allen-Bradley carbon resistors as thermal sensors, as developed at Cornell [22]. T-map systems commonly in use for many years at DESY include a fixed type for single-cell cavities with 768 sensors [23], and a rotating system for 9-cell cavities with 128 sensors [24]. A fixed thermometry system for 9-cell cavities with four sensors around each equator and a few sensors on the endgroups has been developed at KEK and was used for tests of STF Tesla-like cavities [25]. Second sound detection has been used at ANL for quench location on split-ring resonators [26]. A selection of new hot spot detection systems are described; these systems vary in coverage, flexibility, and in the number of cavity tests required to extract useful T-map information.

Thermometry with Cernox Sensors

A system of Cernox temperature sensors has been developed at Fermilab [27] and used for quench location. Up to 32 sensors may be attached as needed to suspect locations; therefore the system is very flexible but also time consuming to install, typically requiring several cavity test cycles to conclusively locate quenches. It is highly portable and suitable for any cavity shape.

Multi-Cell Fixed Thermometry Systems

New multi-cell T-map systems have also been developed. A new 2-cell system at JLab was recently commissioned [28], with 160 Allen-Bradley sensors installed around each of the two equators. Understanding cavity behavior requires two cooldowns: one to measure the TM_{010} passband modes and determine within two the limiting cells, then a second after the T-map installation to measure the temperature distribution of the limiting cell. At LANL, a new 9-cell T-map system has been developed [29] which employs 4608 Allen-Bradley sensors and a multiplexing scheme to map an entire 9-cell cavity in a single test yet limit the number of cables leaving the cryostat. The preliminary results are very promising. A 9-cell T-map system at Fermilab using 8640 diodes as a multiplexed thermometer array is under development [30]. All of these multi-cell T-maps are specifically designed for the Tesla cavity shape.

Second Sound

Cornell has developed a new quench location system using second sound sensors [31]. Second sound is a thermal wave which can propagate only in superfluid helium. It is generated when a heat pulse is transmitted from a heat source, such as a quench, through superfluid helium. In this system, eight sensors detect the arrival of the temperature oscillation, and the location is determined from the relative timing of the arrival of the oscillation from different sensors. This simple system is suitable for any cavity shape or number of cells and can locate quenches in a single cavity test.

Optical Inspection

A resurgence of interest in optical inspection occurred within the last year when several cavities with hard quench limitation in the 15-20 MV/m range, were observed to have surface defects correlated with hot spots, using a new optical inspection system developed by Kyoto University/KEK with a clever lighting technique and excellent resolution.

This optical system [32] consists of an integrated camera, mirror, and lighting system on a fixed rod; the cavity is moved longitudinally and axially with respect to the camera system. The lighting is provided by a series of electroluminescent strips, which provide lighting with low glare on the highly polished surface. These strips can be turned off and on, and the resulting shadows studied for an effective 3D image of the depth or height of the defect. The camera resolution is about 7 µm.

An optical inspection system employed regularly at JLab [13] includes a Questar long-distance microscope and mirror to inspect any cavity inner surface. This system uses electroluminescent lighting; the images are converted to black-and-white for clarity.

Additional optical inspection systems are in use or under development at other labs.

Improving Surface Quality

Because many of the cavity-limiting surface defects found by thermometry and optical inspection are located in the heat-affected zone of the electron-beam welds, weld properties are under intense scrutiny. Understanding which weld parameters might contribute to creating such defects, and ultimately eliminating the defect occurrence, is critical to improving the yield of high-gradient cavities. Note that cavities with such defects are largely from new cavity manufacturers.

One group has attempted to reproduce these features by electron-beam welding high-quality niobium scraps, leftover from cavity fabrication, and electropolishing the samples using standard techniques [33]. Several such samples have been produced, and many have features which appear, with a 3D microscope, similar to those found in real cavities. It remains to be seen how similar these defects really are to those found on cavities. If the real defects are reproducible in the lab, they can be systematically studied and the information fed back to cavity fabricators. In time, the overall cavity surface quality may be improved in a manner similar to that of the niobium sheets resulting from eddy current scanning.

CONCLUSIONS AND OUTLOOK

Highlights of the rich R&D activity in the quest for high gradient and reduced cost have been described. Very high gradients have been measured in niobium SRF cavities: more than 50 MV/m in single-cell cavities of various shapes, and more than 35 MV/m in several 9-cell Tesla-shape cavities. Several promising new results from large-grain 9-cell cavities and hydroformed cavities address the cost and reliability issues of these cavities. Several cavities which have been limited to 15-20 MV/m by hard quench have been studied using various techniques, and the outlook is good that useful information can be fed back to cavity manufacturers to improve the yield of high-gradient cavities over time. Surface treatment is crucial for optimum performance, and several promising studies on final preparation methods have been found to sharply reduce field emission. One study on trapped vortices may partially explain Q-drop, which causes poor cavity performance and high power dissipation at high gradient. Finally, a cavity made of bulk niobium and a layered composite at the RF surface has been proposed to break the critical magnetic field limitation of niobium and shows promising new results.

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