GRADIENT R&D IN THE U.S. – OVERVIEW AND SUMMARY*

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Abstract

Over the past few years, significant effort has been made to systematically improve multi-cell cavity accelerating gradients, driven in large part by the requirements of the ILC, for which the reproducible achievement of high gradients is a prerequisite. Substantial progress has been made by teams at Cornell University, Fermilab, and Jefferson Lab, in pushing gradients to higher values and in achieving this performance on a more regular basis. Development of improved diagnostic and inspection techniques along with the utilization of both localized and global repair tools have helped enable this improvement. Likewise, processing and assembly procedures that led to a lower incidence of field emission have facilitated this progress. The present status of cavity performance will be presented along with its evolution, and examples of the role the aforementioned techniques and tools have played in achieving this performance.

INTRODUCTION

In recent years, significant effort and progress has been made in improving the achieved gradients and gradient yield in multi-cell 1.3GHz cavities, motivated by the requirements of the proposed International Linear Collider (ILC), which requires that gradients of 35MV/m and $Q_0 \geq 8 \times 10^9$ be achieved in vertical test. These efforts have proceeded along several fronts :

- Optimization of electropolshing (EP) processing
- Control of field emission
- Detection of quench origins
- Repair techniques
- New processing methods
- Alternate shapes

These efforts, over time, have improved cavity performance. In Fig. 1, the maximum achieved gradient of all 9-cell cavities processed and tested by Cornell University, Fermilab/Argonne (FNAL/ANL) and Jefferson Lab (JLab) over the past ~4 years are shown. Steady improvement is noted. The dotted lines represent a 5-period moving average of the data, and while there is certainly scatter in the data, a general trend of improvement is clear.

CAVITY GRADIENT YIELD

The cavity gradient yield is defined as the fraction of cavities in a sample that achieve a particular gradient value[1]. This yield has been calculated for cavities that undergo a single process/test cycle (so-called "first-pass yield") and also for cavities that initially do not meet the ILC performance and subsequently receive an additional round of processing/test (so-called "second–pass yield"). The yield of cavities processed and tested by the collaborating institutions of JLab, DESY, and KEK, that exceed 30MV/m after their first process/test cycle, has improved over time to 50%, while 30% of cavities reach the ILC specification of 35MV/m. Figure. 2 shows the yield of achieved cavity gradients over time, for this scenario.

When one considers the effect of an additional process/test cycle applied to cavities that do not initially reach the ILC performance specification, the yield improves substantially. Under this scenario, fully 70% of cavities reach or exceed 30 MV/m, while over 50% reach the ILC performance goal (Fig. 3).

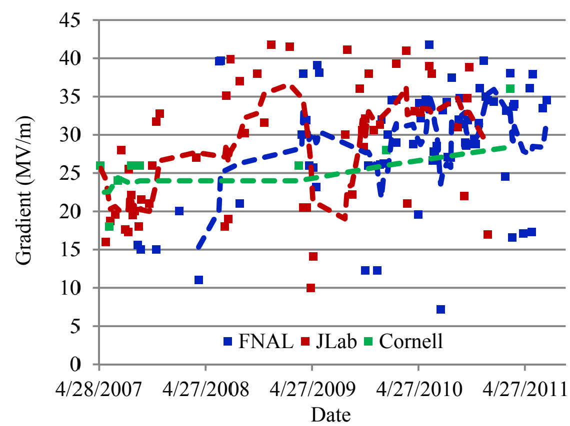

Figure 1: Cavity gradients as a function of time for cavities processed and tested at Cornell, JLab, and FNAL. The dotted lines, representing a 5-point moving average, show general improvement.

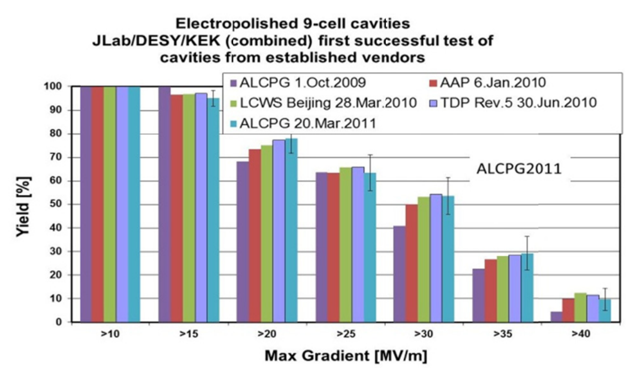

Figure 2: Cavity gradient yield after first process and test cycle. The individual vertical bars represent the yield achieved as development has progressed over time.

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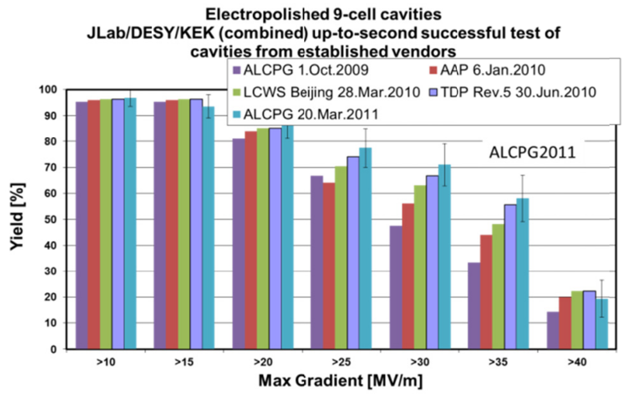

Figure 3: Cavity gradient yield after second process and test cycle.

OVERVIEW OF R&D EFFORTS

The improvement in cavity gradients described above and shown in Fig. 1 has been the result of a number of efforts and activities pursued by the ILC-America's collaboration of Cornell, FNAL/ANL, and JLab. Some of them are briefly summarized here.

Optimization of EP Processing

Parameters for electropolishing of nine-cell ILC-style cavities have evolved over the past several years based on both empirical studies and directed studies of the EP electrochemistry[2][3], and as a result have become reasonably stable, yielding generally high-performance cavities. The need to control and indeed, reduce, acid temperature, was also recognized and addressed. JLab controls acid temperature by actively cooing the outer cavity surface during the electropolishing process, while FNAL/ANL achieves this goal by controlling the acid temperature. Both labs have reduced the temperature of the electrolyte during the final "light" EP step to 25-30°C.

Monitoring and control of EP parameters has been instituted. The temperature of the cavity and the acid mixture, in addition to voltage and current/current density, are controlled and recorded on a routine basis. As a result, unwanted variations in process parameters that lead to performance variations or degradation have been minimized. Figure 4 gives an example of the process control/logging program in use at the FNAL/ANL facility.

Field Emission Control

Field emission has traditionally been a significant source of cavity performance limitations, especially at high gradients where peak surface electric fields are in excess of 50MV/m. However, recent advances in cleaning and processing techniques have reduced the instances of field emission, improved its onset (moving it to higher fields), or reduced its intensity so that it no longer is responsible for limiting cavity gradients.

In particular, at JLab and FNAL/ANL the following improvements have been adopted:

- Ultra-sonic cleaning w/ detergent after EP
- Longer high-pressure rinsing (overnight)
- Cleaning of HOM filters
- Controlled (slow) cavity evacuation
- Optimized/improved tooling
- Consistency of assembly staff

Taken together these measures have considerably reduced the impact of FE, to the point where only 10-20% of cavities are limited by field emission loading.

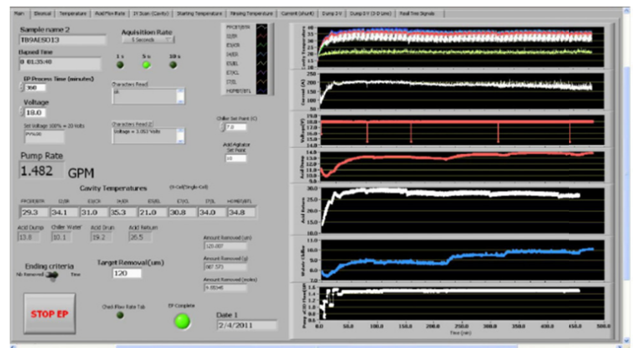

Figure 4: Process control/monitoring at the FNAL/ANL EP facility.

Detection of Quench Origins

An active and fruitful area of research has been the development and refinement of techniques to allow for the straightforward and simple detection of the physical locations of quench origins. All collaborating laboratories are using a combination of Oscillating Superleak Transducers (OST)[4] and thermometry [5][6] to locate quench origins to a few mm accuracy.

Once these locations have been determined, the interior surfaces of the cavity are examined using optical inspection systems such as the Kyoto camera system[7][8] or Questar microscope. Often features or defects are found at these locations.

For example, Fig. 5 shows a 200-300μm diameter defect (determined to be a "bump", or protrusion) found on the interior surface of cavity AES003, which quenched at 20 MV/m. At other times, no observable feature is found, such as the area of cavity TB9RI024 shown in Fig. 6, which was determined to be the location of the quench in this cavity at 29MV/m. More confounding, perhaps, was the observation of a nearly 1000μm feature found in single-cell cavity TE1AES004, which quenched at 40MV/m, but not at the location of this feature! (Fig. 7)

Observations of the locations of quench origins for a wide number of cavities with varying performance limitations leads to a general conclusion that cavities that are limited to low gradients, (less than, say, 20-25 MV/m) exhibit an identifiable (and usually large) feature (defect) at the quench origin. Conversely, cavities that quench at higher gradients (30-33MV/m or more), often do not show such a feature, and the quench origin appears unremarkable.

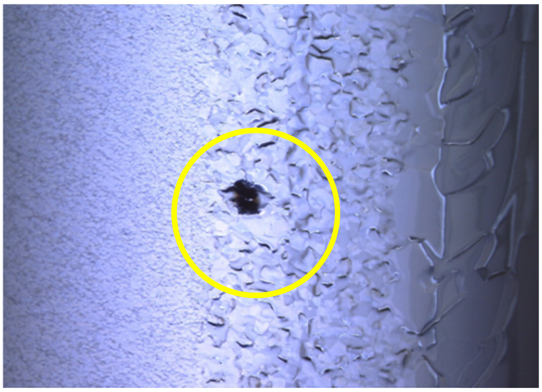

Figure 5: Defect found at quench origin in cavity AES003, which was limited to 20MV/m.

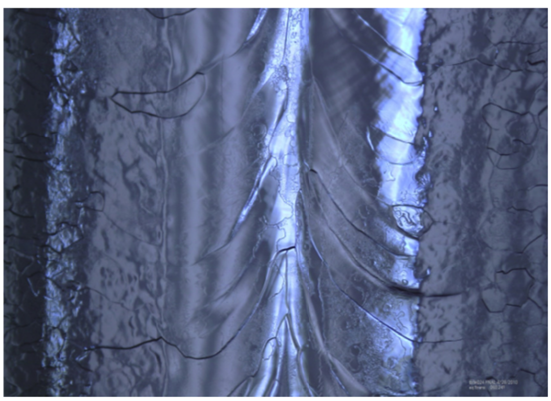

Figure 6: Area of cavity TB9RI024 which was the site of a 29MV/m quench. No discernable "feature" is seen.

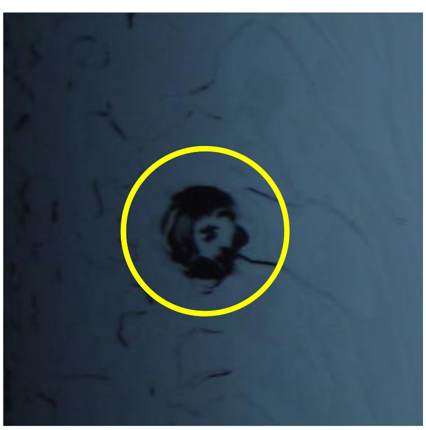

Figure 7: Feature with a diameter of ~1000µm found on cavity TE1AES004 which quenched at 40MV/m, but not at the location of this feature.

Repair Techniques

The ability to recover a cavity whose performance does not meet specifications through mitigation of a known defect provides a valuable mechanism for improving cavity gradient yield. This can be done by utilizing either global methods applied to the entire cavity RF surface, or local methods directed specifically at the site of the quench origin. Examples of local repair techniques being developed are :

- Laser re-melting (FNAL)
- Electron Beam (EB) re-melting (JLab)
- Local grinding (KEK)

Global methods include :

- Centrifugal Barrel Polishing
- Additional EP

Apart from additional EP, all of these methods are relatively new and under active development. For example, the local grinding technique developed by KEK[9][10] was applied to cavity AES003, which quenched at 20MV/m due to a defect (shown in Fig. 5). The defect was ground and polished, and the cavity then received a 50µm EP processing cycle, followed by HPR. The repaired area is shown in Fig. 8. Almost no traces of the original defect can be seen. Upon subsequent vertical test, the cavity reached the ILC gradient specification (Fig. 9), and was now quench-limited at a different location, indicating a successful repair.

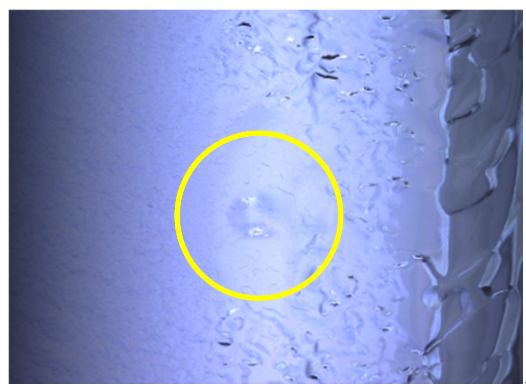

Figure 8: Site of the original defect in cavity AES003 (shown in Fig. 5) that had limited it to 20MV/m.

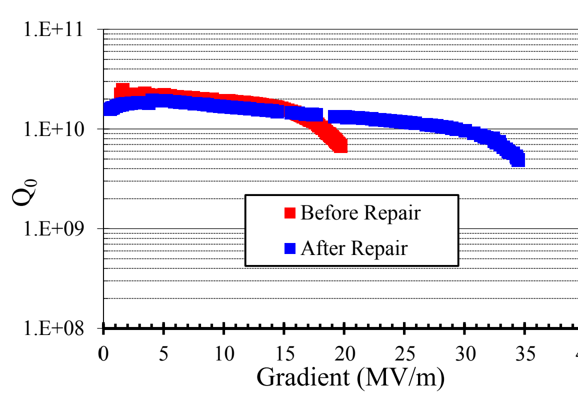

Figure 9: Performance of cavity AES003 before (red) and after (blue) repair by local grinding. Gradient has improved from 20 to 35MV/m.

Another repair technique that has been pursued is Centrifugal Barrel Polishing (aka "tumbling")[11][12]. Cornell, FNAL, and JLab have all acquired and installed CBP facilities (Fig. 10), and are beginning to develop techniques and procedures for use in cavity surface processing. Cavity TB9ACC015 was quench limited to 19MV/m during vertical test at JLab. Thermometry was used to determine the quench location and optical inspection confirmed the presence there of a defect, a 200μm diameter pit.

Figure 10: Centrifugal Barrel Polishing (CBP) machine in use at FNAL. Identical machines have been acquired by Cornell and JLab.

The cavity was subsequently delivered to FNAL where it underwent CBP end EP processing. A total of 150μm of material was removed by CBP, followed by 40μm of material removal through EP (in two stages). The cavity received a 3hour 800°C H degassing between the two EP steps, and was baked at 120°C for 48hours before vertical test.

Optical inspection revealed that the original defect was completely removed by these process steps (Fig. 11). Upon vertical test, the cavity reached 35MV/m with a Q_0 at quench field > 1 x 10^{10} – meeting the ILC performance specifications, and exhibiting substantial improvement from the 19MV/m reached before repair (Fig. 12).

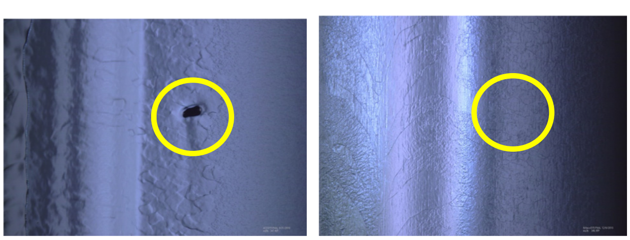

Figure 11: Quench-inducing defect in cavity TB9ACC015 before (left) and after (right) repair by CBP and EP.

Yet another potential repair technique is laser re-melting[13], a technique wherein a collimated laser beam is used to melt the cavity surface in the vicinity of a defect, with the expectation that upon cooing/solidifying, the surface topography has been improved so that magnetic field enhancement is reduced and higher gradients can be achieved. This has been successfully accomplished on a single cell cavity at FNAL, whose performance was improved from 36 to almost 40MV/m. Recent attempts using this technique to improve the performance of a 9-cell cavity limited to 12MV/m have so far been unsuccessful, with the repaired cavity exhibiting a strong "Q-switch" behaviour at 4MV/m.

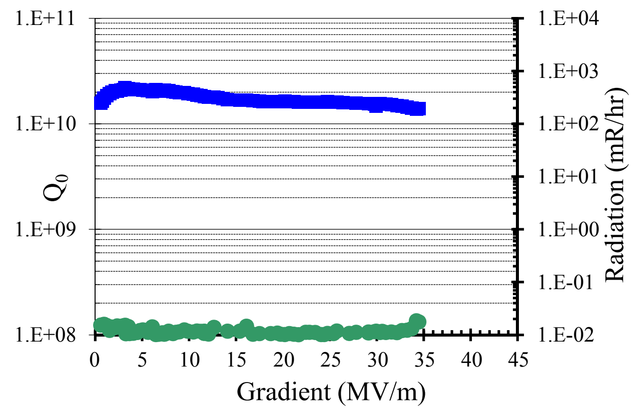

Figure 12: Performance of cavity TB9ACC015 after repair by CBP and EP.

New Processing Techniques

Recognizing that it is possible that some cavity performance limitations could be an artefact of the current baseline processing techniques, there has been effort directed at developing either alternative processing techniques or alternative implementations of the current baseline (EP) process. An additional motivation is to reduce the cost, complexity, or hazardous nature and environmental impact of the current baseline process. Centrifugal Barrel Polishing has already been discussed in the context of repair techniques, but has also been used as an alternative to the so-called "bulk" EP process.

Cavity TE1ACC004, a single-cell cavity, received a bulk CBP which removed 120μm of material. This was followed by a light EP (40μm), then a H degassing at 800°C for 3hrs. A standard cavity preparation (light EP, HP, assembly, and 120°C bake) then followed. During vertical test (Fig. 13), the cavity reached 40MV/m, with a Q_0 at this quench limit of 1 x 10^{10}, without field emission, surpassing the ILC performance requirements.

At Cornell and JLab, efforts have been underway for some time to develop Vertical Electropolishing (VEP) of cavities [14][15](see Fig. 14). This technique has the potential to simplify the mechanical operation of the current EP process by eliminating the complexity inherent in a rotating system that must accommodate both electrical contacts and fluid transfer capabilities. It may also prove easier to provide sufficient cooling to the cavity outer surface needed to maintain appropriate electrolyte temperature. Results have been encouraging, with 9-cell cavity A9, processed and tested at Cornell recently reaching 36MV/m and exceeding the ILC gradient specification. Efforts are currently being pursed at Cornell to reduce the cavity surface resistance (improve Q_0) that result from this process, primarily by reducing the electrolyte temperature to 20-25°C and increasing the applied voltage. A single-cell cavity recently processed with these optimized parameters exhibited excellent residual surface resistance of less than 1nΩ !

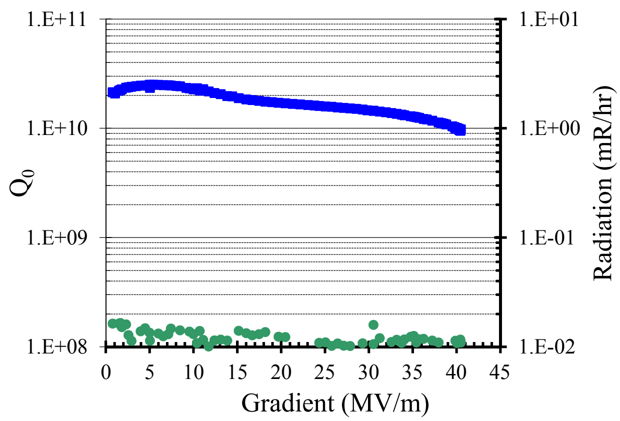

Figure 13: Performance of cavity TE1ACC004 after bulk material removal performed by CBP.

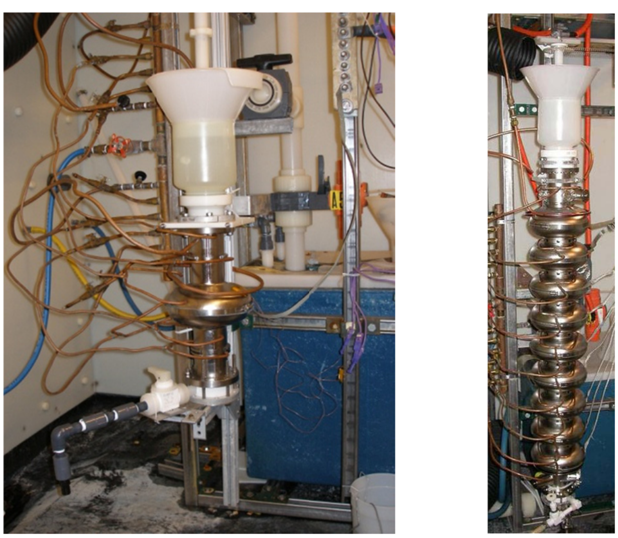

Figure 14: The VEP setup at Cornell University for single-cell cavities (left) and 9-cell cavities (right).

Alternate Cavity Shapes

The existing ILC cavity design (the so–called "TESLA" shape) is practically limited to accelerating gradients of about 42-45 MV/m. At these gradients, the peak magnetic field H_{pk} approaches the theoretical limit of 180-190mT. In order to achieve higher accelerating fields, a cavity shape with a lower H_{pk}/E_{acc} ratio is required, in order to keep the peak magnetic fields on the cavity walls below this critical value. Both Cornell and KEK have been developing cavity designs that utilize this to theoretically achieve gradients in excess of 50 MV/m.

The ICHIRO cavity shape developed by KEK[16] has reached 50 MV/m performance in single-cell tests, while multi-cell ICHIRO cavity #7 has reached 40 MV/m. Likewise, the re-entrant cavity shape being developed by Cornell[17] has been shown to achieve extremely high gradients as a single-cell cavity, and efforts are progressing toward achievement of similar gradients in a 9-cell version. Currently a gradient of 30MV/m has been achieved in a re-entrant multi-cell cavity.

These alternate cavity designs/shapes do pose additional challenges. Due to their design, they achieve low H_{pk}/E_{acc} ratios, but at the expense of increasing the E_{pk}/E_{acc} ratio. As a result, surface fields may be in excess of 100MV/m, and susceptibility to limitations due to field emission increases as smaller and smaller contaminants may be more likely to become active field emitters at these field levels. Improved cleaning techniques (that also address the potentially inherent difficulty in cleaning these "flattened" cavity shapes) may need to be developed in order to fully take advantage of these designs.

SUMMARY AND OUTLOOK

Significant progress in reaching high cavity gradients has been made by labs in the U.S. The achievement of the ILC performance specification of 35MV/m is becoming routine. However, this achievement is far from predictable or reproducible. Inspection of Fig. 1 confirms that there is a significant degree of scatter in the achieved gradients, representing a level of non-uniformity in either the raw materials, fabrication procedures, or surface processing, that is un-accounted for and detrimentally affects cavity performance.

There is a growing consensus that low to medium field quenches are due to an observable feature or defect on the cavity inner surface. Optical inspections of these quench locations have confirmed the presence of such features in all recent cases. It is plausible that such defects arise from problems with the raw material preparation or fabrication/welding processes during cavity manufacture. Better control of those factors would likely result in the elimination of low to medium-field quenches in cavities.

On the other hand, it appears that for higher field quenches, there is no consistency in the results of optical inspections of quench locations – observable defects are often not found. While there are proposed mechanisms for understanding and explaining the role that topographic defects play in generating quenches[18], these mechanisms would not appear to be relevant in the case where an observed defect (i.e., topographic non-uniformity) is not observed. Therefore further study is required to understand the source of the increased loss mechanism responsible for these quenches, and relate it to cavity material or surface preparation parameters. It is crucial to develop an enhanced understanding of how various surface preparations affect the properties of the cavity RF surface, and then to understand how specific surface properties affect cavity global performance. Only in this manner is there some hope of eliminating, predicting, or reducing the occurrences of higher-field quenches. This would appear to be a direction worthy of increased attention.

Development of new processing techniques that simplify, make safer, or make more economical cavity surface preparation is being pursued with vigour. While at the present time no technique is available that eliminates the use of dangerous and high environmental impact acids, significant reductions in their amount may be possible through these new techniques, while at the same time yielding a more predictable and uniform substrate for the traditional light EP final processing step.

Various repair techniques under active development have been shown to be able to substantially improve cavity performance, in some cases meeting the ILC performance goals. While useful, they do not offer an economically appropriate means for increasing or achieving the necessary cavity gradient yield for a project like the ILC, so should perhaps be reserved for use in R&D or small-scale production projects.

The almost-routine achievement of gradients around 35MV/m is evidence that a high degree of optimization and refinement has taken place recently in a broad set of categories – from raw material production, cavity fabrication, cavity surface processing, and enhanced cleaning and assembly techniques. This has provided a solid foundation for producing cavities that can reach high gradients.

ACKNOWLEDGMENTS

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