Gradient R&D in the US – Overview and Summary

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(on behalf of collaborators at ANL, Cornell, FNAL, JLab, and KEK)

Introduction

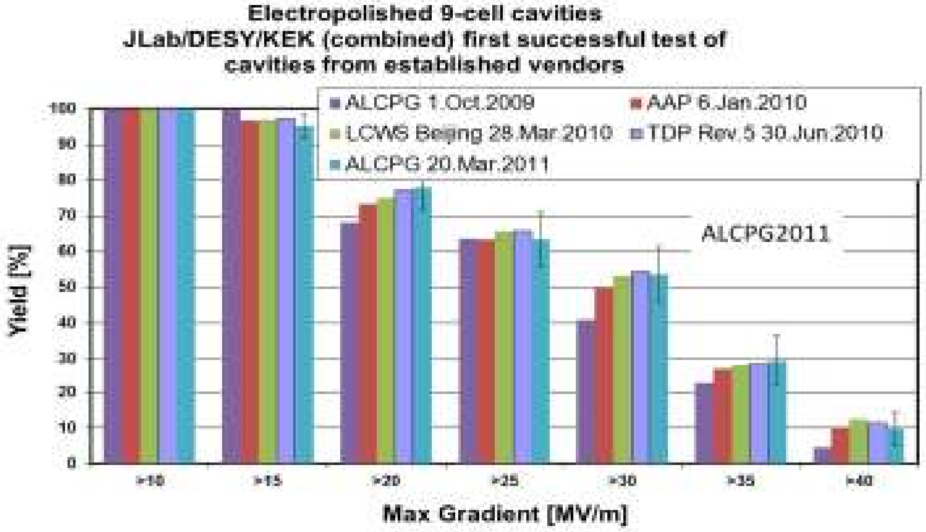
Significant efforts have been made in recent years to improve multi-cell cavity gradients, driven primarily by ILC requirements (35MV/m in vertical test). Goal is to increase gradient, and gradient yield.

Here in the U.S. this effort has proceeded along several axes :

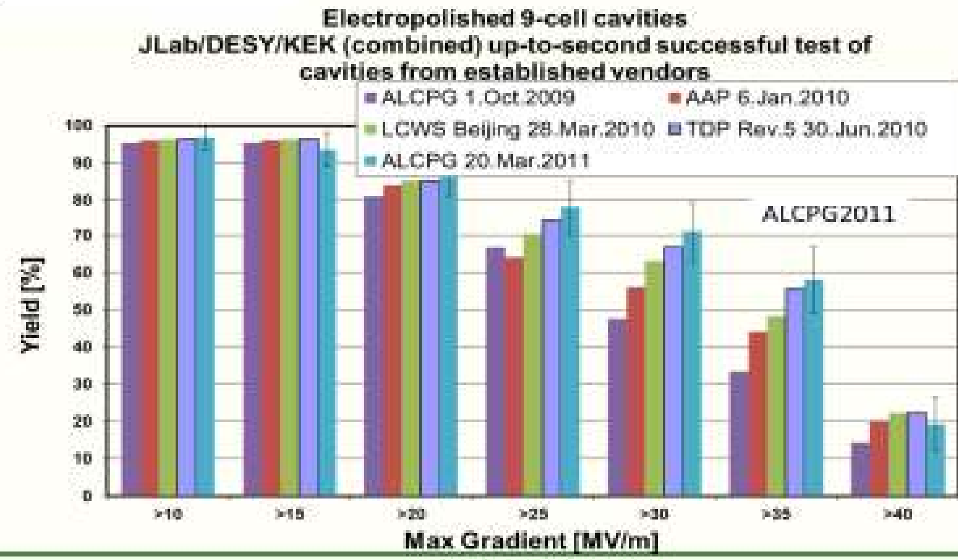
- Optimization of EP Processing
- Control of Field Emission
- Detection of Quench Origins (defects/features)
- Repair Techniques
- New Processing Methods
- Alternate Shapes

Work is ongoing, and steady progress is being made, and will be summarized here.

Cavity Gradient Yield



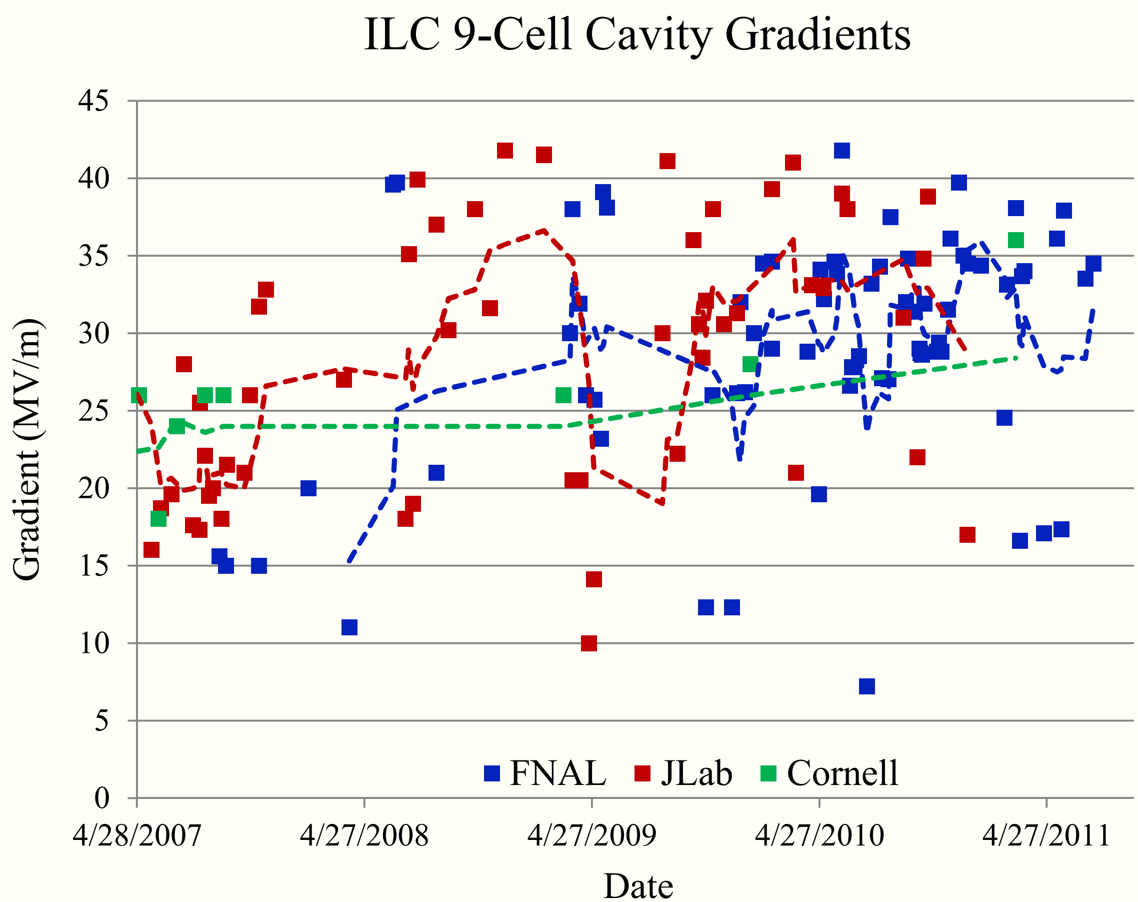
Over time, yield of cavities reaching > 30MV/m after 1st test improves markedly, reaching 50%; 30% reach the ILC spec.



When one considers the effect of a second process/test cycle, the yield of cavities reaching > 30MV/m now reaches 70%, and over 50% reach the ILC spec.

Courtesy C. Ginsburg

Cavity Gradient Progression



Steady (and remarkably similar) progress in gradients over time

(5-period moving average shown)

EP Optimization

Parameters for EP processing have been optimized and stabilized over the course of several years, based on empirical observations of cavity performance, and also through directed studies. Control of acid temperature, and lower acid temperature, has been recognized as crucial.

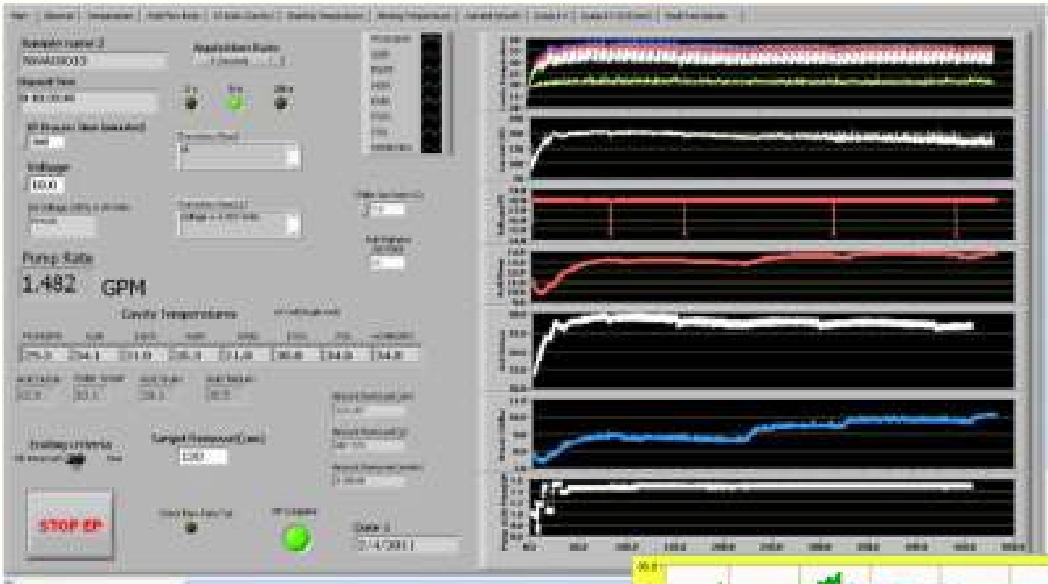
JLab :

- **Cell temperature control (active cooling of cavity)**
  - **Heavy (bulk) EP : 30-35°C**
  - **Light EP : 25-30°C**
- **Constant voltage**
  - **Nominal 14.5V (12-17V allowable range)**
- **Continuous current oscillation**

FNAL/ANL :

- **Cell temperature control (acid temp control)**
  - **Bulk & Light EP : 25-30°C**
- **Constant voltage**
  - **Nominal 18V (after results at 14V gave low Q_0 values)**
- **Continuous current oscillation**

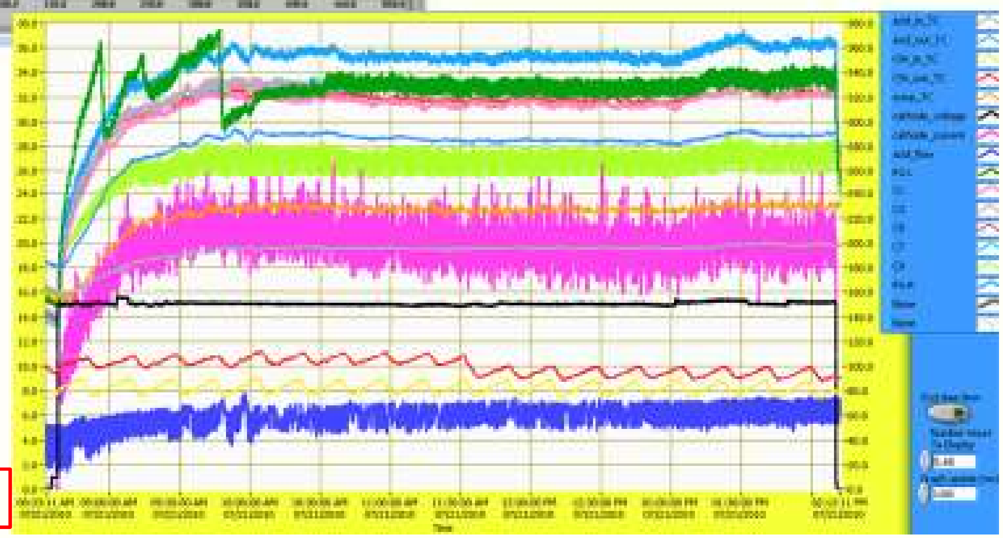
EP Optimization



EP parameters such as acid temperature, cavity temperature(s) and voltage and current are routinely monitored and controlled. The operation is reproducible and routine.

FNAL/ANL EP process monitoring

JLab EP process monitoring



Courtesy R. Geng

Control of Field Emission

Improvements in processing/cleaning techniques have helped reduce the number of cavities limited by FE and/or increase the onset of FE.

- US cleaning w/detergent after final EP
- Longer HPR (overnight)
- HOM brush cleaning
- Controlled (slow) pumpdown
- Improved/optimized tooling
- Staff consistency

However, FE still does occur, and sometimes it occurs “spontaneously” and “permanently” degrades cavity performance.

This “spontaneous” occurrence has been observed at least half a dozen times in the last couple of years. It often requires additional processing/remediation beyond HPR to recover performance.

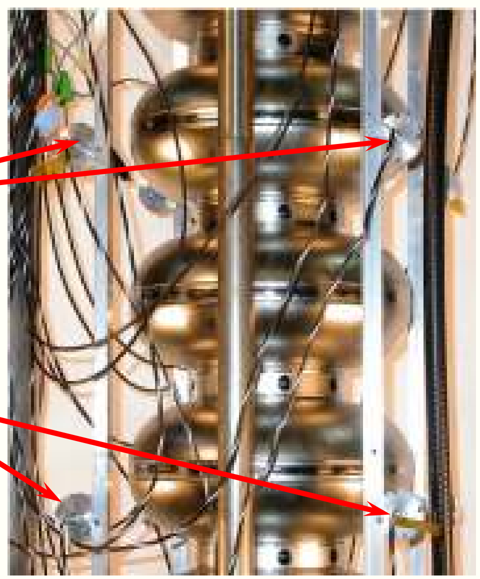
Detection of Quench Origins

All labs are now using a combination of thermometry and second-sound detectors (OST) to localize quench origins.

Second sound detectors (OST's)

Fast Thermometry System (FTS) bands on equator at FNAL

OST's mounted on 9-cell cavity at Cornell



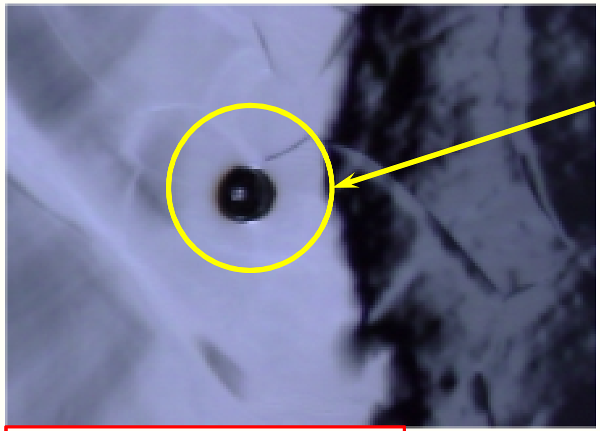
2-cell T-Map system mounted on cells 3 & 7 of a 9-cell cavity at JLab

Courtesy Z. Conway, R. Geng, D. Sergatskov

Observation of Quench Origins

Once quench origins are detected and located, the interior surface of the cavity is inspected. All labs now have optical inspection capabilities (Kyoto system, Questar system). Often, “features” or “defects” are observed.

Cavity TB9ACC017, quenched at 12 MV/m

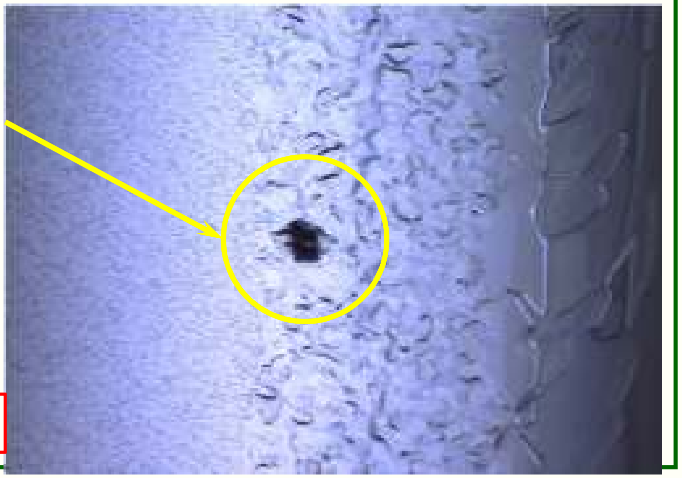


After EP ~ 230μm diameter feature (pit?)

Courtesy D. Sergatskov

Cavity AES003, quenched at 20 MV/m

Bump, diameter ~200-300μm



Courtesy K. Watanabe

Observation of Quench Origins

Sometimes nothing (obvious) is observed.

Cavity TB9RI024, quenched at 29 MV/m.

Cavity received additional (light) EP, then reached 36MV/m.

Courtesy D. Sergatskov

Sometimes there is something obvious - but not the cause/location of the quench!

Cavity TE1AES004, quenched at 40 MV/m!

Defect is pit, ~1000μm (1mm!) in diameter.

Courtesy M. Ge, G. Wu

Repair Techniques

Once defects are found, especially in low-performing cavities, it would be advantageous to be able to eliminate them – i.e., "repair" the cavity – using either "global" or "local" methods.

Various techniques have been or are being developed :

Local Repair:

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

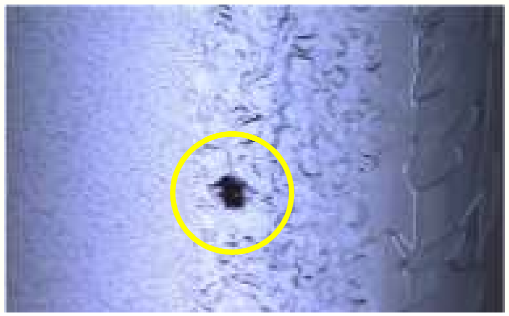
Global Repair :

- CBP (aka "tumbling") – also considered as an alternative to traditional bulk chemical processing
- Additional light EP (not really new, of course)
- Dressed cavity EP

Repair Techniques – Local Grinding

Technique developed at KEK; grinder is inserted into cavity and is directed at site of defect.

Recall cavity AES003, quench limited to 20 MV/m.

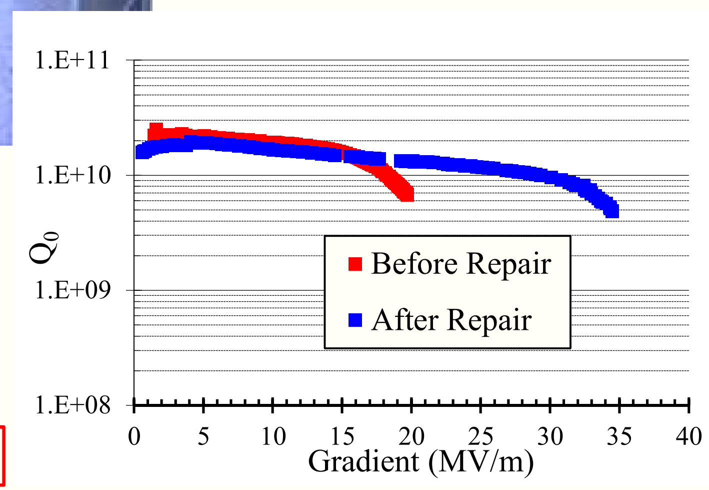


Bump, diameter ~200-300μm

After grinding and 50μm EP

After grinding

After repair and EP/HPR cavity now meets ILC gradient spec (quench limited, new location).



Courtesy K. Watanabe

Repair Techniques – CBP/Tumbling

Like optical inspection and thermometry, all US labs now have CBP apparatus. These have been used for alternative process development and also as a "repair" tool.

Preliminary R&D on CBP has identified a process that can yield mirror like finishes, and can eliminate the need for bulk EP.

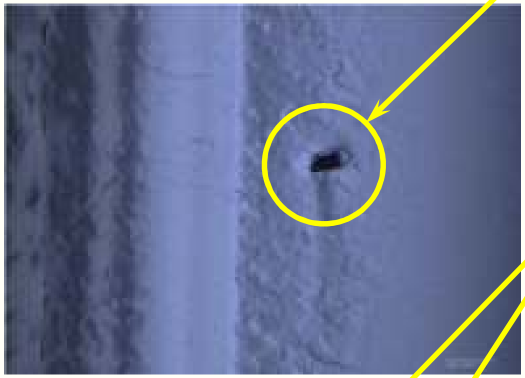
However, so far between 40 and 20μm of material still needs to be removed by chemistry processing (EP).

Courtesy C. Cooper

Repair Techniques – CBP/Tumbling

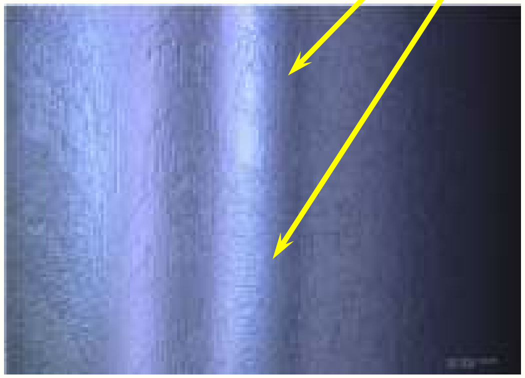
Cavity TB9ACC015 tested at JLab, quench limited to 19MV/m. Thermometry identified a hot spot; optical inspection confirms defect at that location.

After EP, 200μm diameter feature (pit) in cell 3 near equator

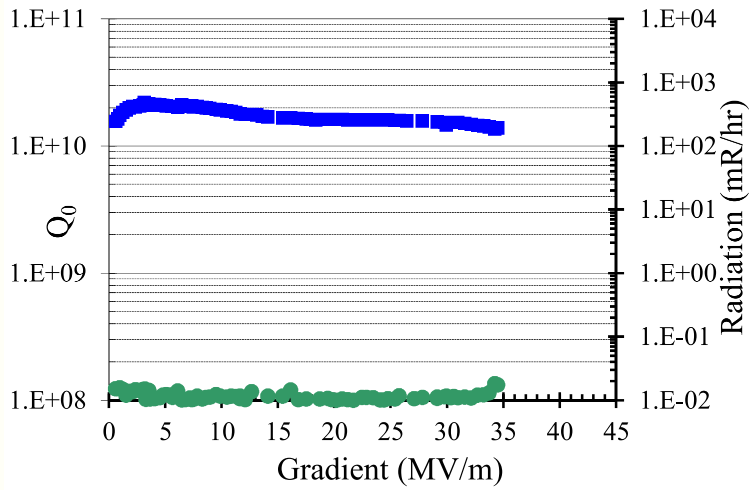


Cavity received ~150μm CBP, light EP, 800°C/3hr HT, light EP, HPR, then 120°C/48hr bake.

After CBP and (total) 40μm EP treatment. Pit has been removed, along with most traces of weld seam/HAZ.



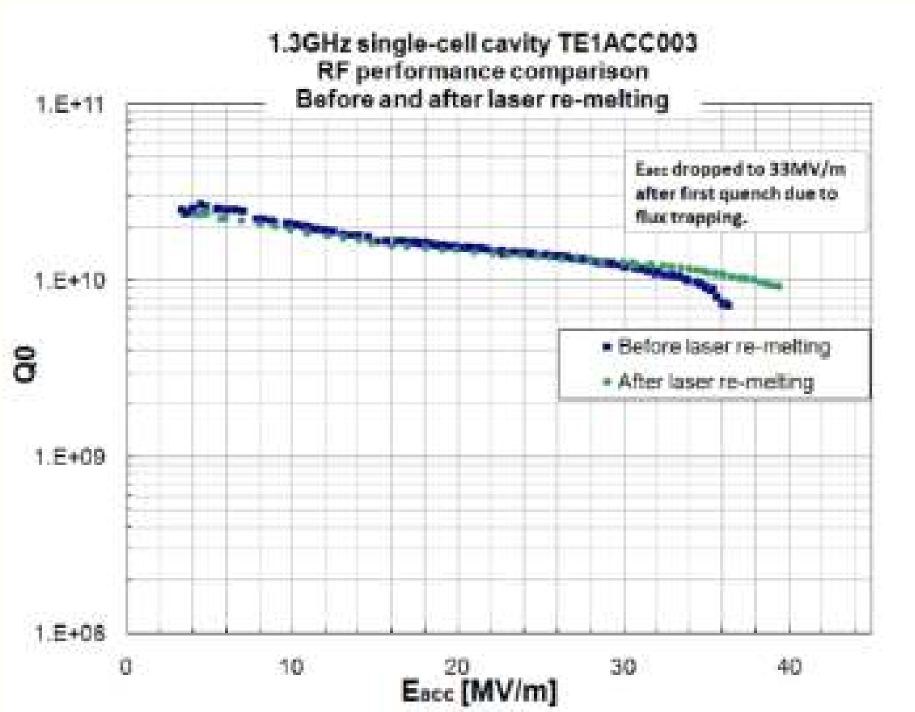
Quench limit improved from 19 to 35MV/m, with Q_0 at quench > 1x 10^{10} – meeting ILC specs!

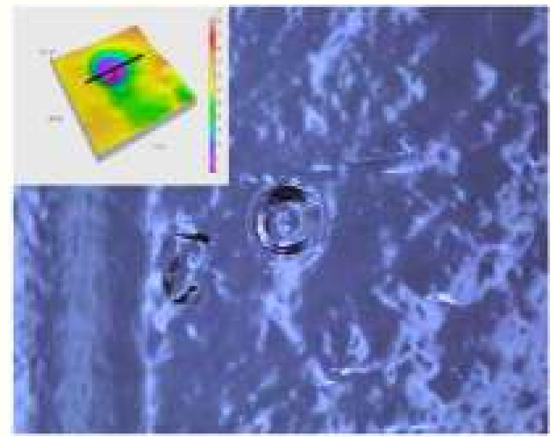


Repair Techniques – Re-Melting

Re-melting (via E-beam or laser) has been successfully attempted on single-cell cavities at JLab (E-Beam) and FNAL (laser).

Laser re-melting example :



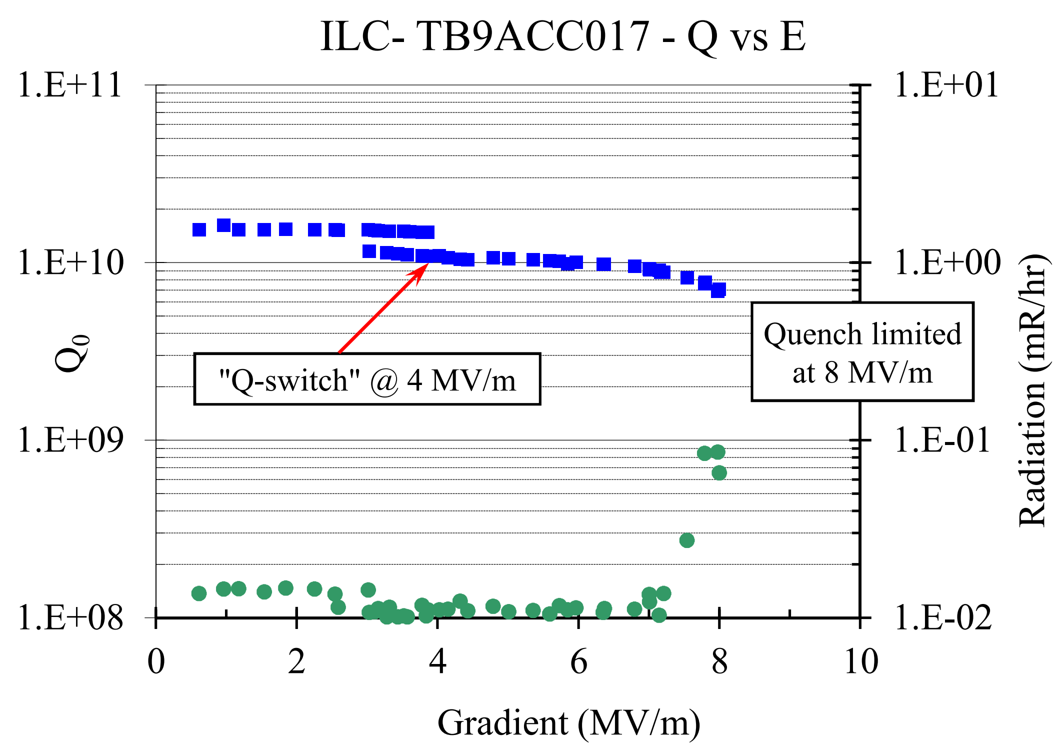


Technique is to be tried next on 9-cell cavity (TB9ACC017) that was limited to 12MV/m.

Courtesy M. Ge, G. Wu

Repair Techniques – Re-Melting

Unfortunately, 1st attempt at adapting this technique to a 9-cell cavity was unsuccessful – cavity exhibited a "Q-switch" and quenches at 8MV/m, with some early FE present.



Clearly, process refinement is needed!

New Processing Techniques – Vertical EP

Vertical electropolishing (VEP) is being studied at Cornell and JLab.

Potential benefits :

- eliminates rotary acid seals
- eliminates sliding electrical contacts
- eliminates some cavity handling tooling
- simplifies the acid plumbing/containment
- easier to provide cooling of external cavity surface, yielding better process control

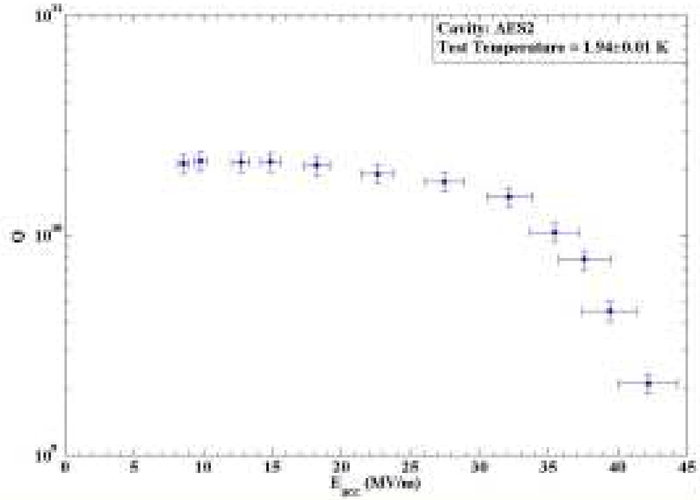
Optimizations pursued at Cornell :

- reduce temperature of acid to 20-25°C
- reduce agitation of electrolyte
- increase voltage during EP from 14 to 17 V

Courtesy Z. Conway, M. Ge, G. Hoffstaetter

New Processing Techniques – Vertical EP

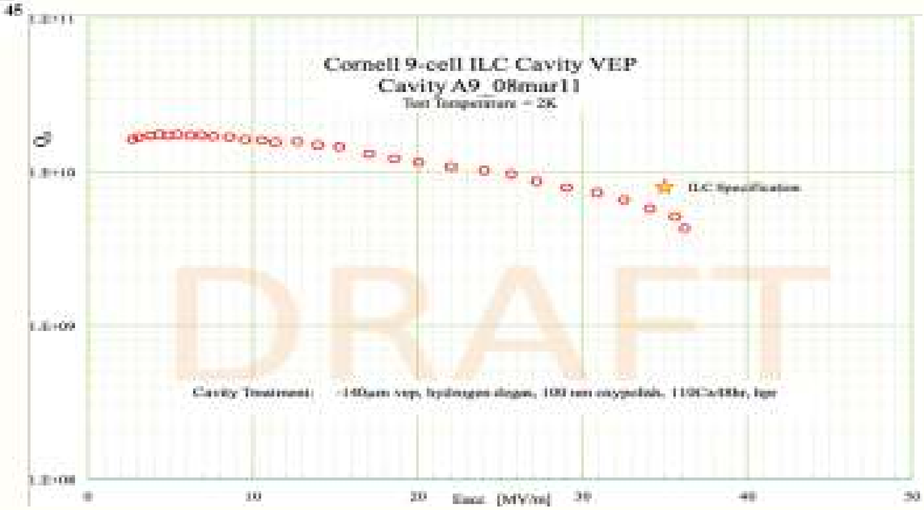
Cornell results show promise:



Single-cell cavity reaches > 40 MV/m, meets ILC gradient and Q_0 spec.

Also, extremely good r_{s0} measured in a SC cavity, ~1 nΩ!

Nine-cell cavity reaches 36MV/m, meeting ILC gradient spec. Q_0 value subsequently improved by higher-voltage VEP.



Courtesy Z. Conway, M. Ge, G. Hoffstaetter, N. Valles

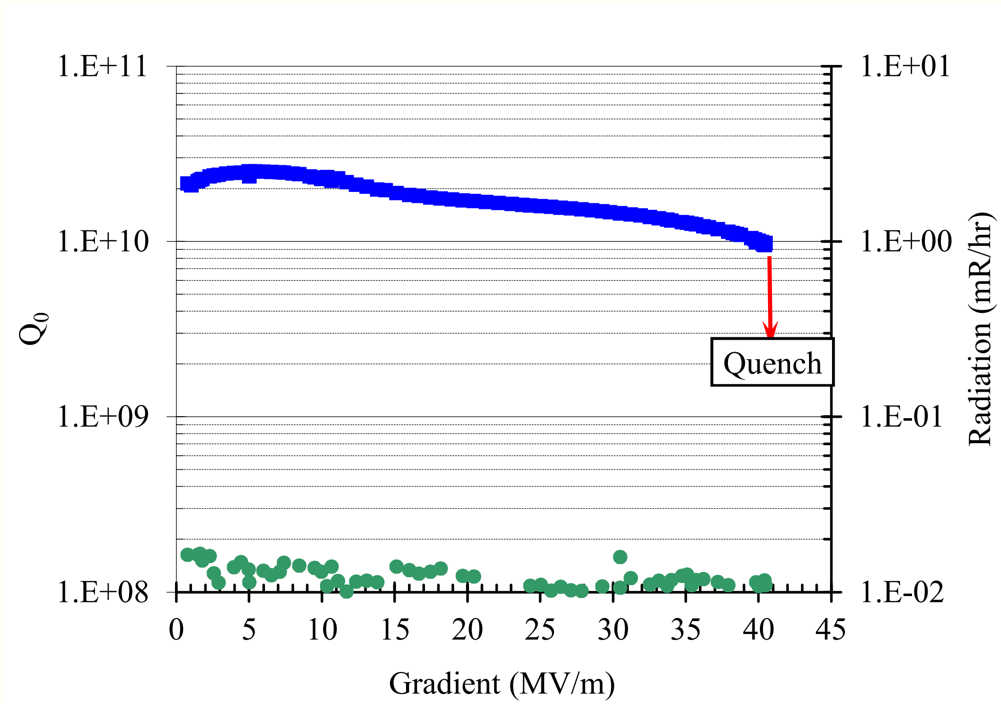
New Processing Techniques – CBP

CBP/tumbling is also being developed as a substitute for bulk EP.

Example : single cell cavity TE1ACC004

- **bulk CBP (120μm)**
- **light EP (40μm)**
- **800°C HT (3hrs)**
- **light EP (20μm)**
- **HPR**
- **120°C bake (40hrs)**

Cavity reached > 40 MV/m, with excellent Q_0, and was quench limited.



Courtesy C. Cooper

Alternate Cavity Shapes

ILC-style cavities are theoretically limited to about 42-45 MV/m (for H_{peak} 180-190mT).

To substantially exceed this value requires a different cavity shape (reducing H_{pk}/E_{acc}, at the expense of increasing E_{pk}/E_{acc}).

This is being pursued at Cornell and KEK/JLab

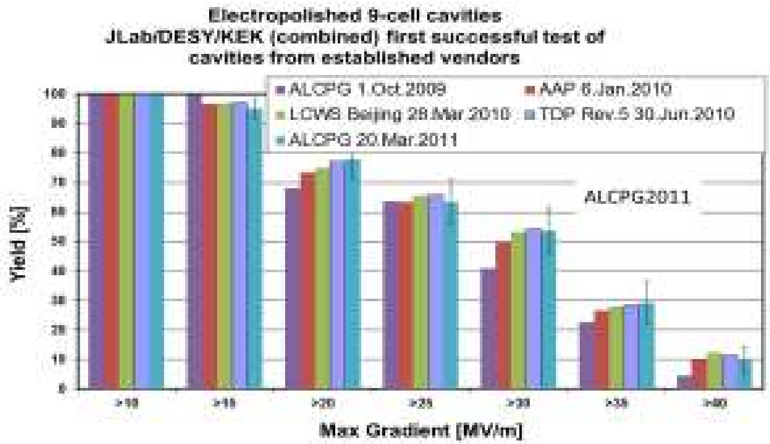
- Cornell : Re-entrant 9-cell cavity reaches 30 MV/m after tumbling to repair defect
- KEK/JLab : Ichiro cavity #7 reaches 40 MV/m, many SC versions reach 50 MV/m

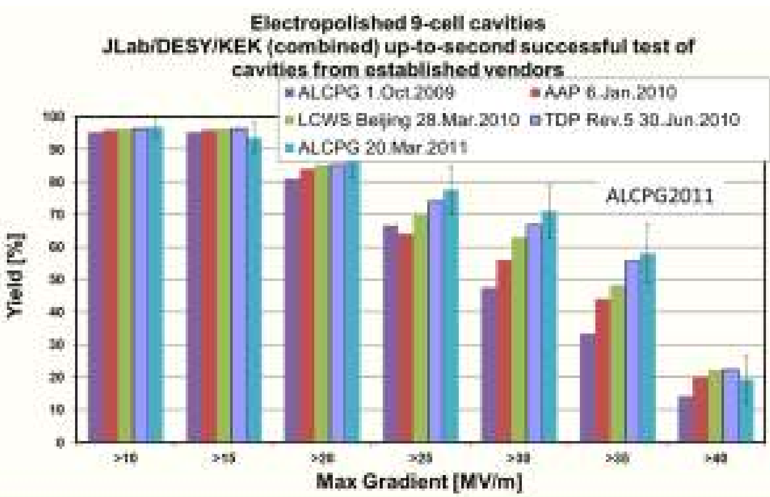
Challenges :

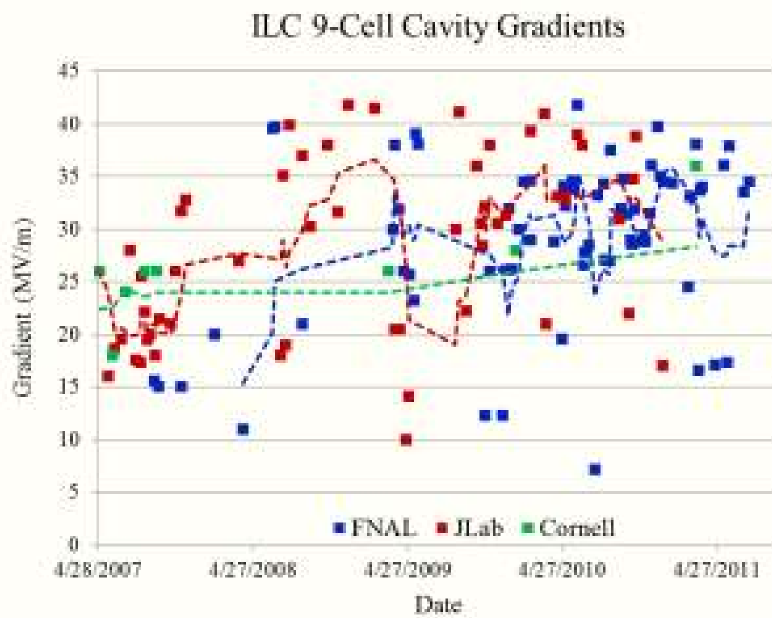
- high (peak) electric fields (> 100 MV/m !) lead to FE susceptibility
- cleaning and processing may be more problematic
- Q-slope, improving Q_0

Summary and Challenges

There has been sustained progress in achieved gradient and gradient yield :







The trend is positive… but the scatter is significant.

Summary and Challenges

Achievement of 35 MV/m is becoming routine (meaning that we don't throw a party when we get there)… **but is far from predictable or reproducible.**

- **Low gradient quench origins are understood – observable defect, arising from welding/fabrication.**
  - **But have we been able to provide useful and usable feedback to vendors regarding why/how it occurs?**

- **High gradient quench origins, where there is no observable (surface) defect, are not well understood.**
  - **What is the mechanism/phenomenology responsible? How do we investigate this (surface/materials studies, cut-outs)?**
    - until we understand this, we can't help vendors make better cavities, or
    - we can't (fully) understand what part of the surface process needs to be optimized/changed, and
    - we don't understand what aspect of the raw material needs to change, and
    - we don't really know what the optimum "repair" is

Summary and Challenges

- Alternative processing techniques (CBP, VEP) are being developed and show promise. But have their own challenges…
  - CBP :
    - Final chemical processing still required
    - Time consuming
  - VEP :
    - Temperature control/oscillations
    - Performance levels

- Field emission is a controllable but ever-present danger.
    - can be an even greater issue as gradients push past 40 MV/m
    - development of improved techniques may be warranted
    - spontaneous FE onset and cavity degradation

- Repair techniques are being refined and becoming mature. Cavity performance improvement to ILC-levels has been demonstrated.
  - But this may not be the most economical route to achieving high yield !

Summary and Challenges

We have already made substantial improvements :

- **high-quality raw materials**
- **well-controlled fabrication**
- **production EP optimization/control**
- **cleaning/rinsing/assembly optimization**

Further performance improvement may require a deeper understanding of :

- **quench origins that are not “visible”**
- **how the RF surface is affected by processing**
- **how RF surface parameters affect cavity performance**

Acknowledgments

The progress made in achieving high gradients in nine-cell ILC cavities fabricated and processed in the US is due to the dedicated efforts of many people at the collaborating institutions and vendors : AES, ANL, Cornell, FNAL, JLab, KEK, NR, and RI. Their hard work is gratefully acknowledged.

In particular, I am extremely indebted to the following colleagues who have contributed information/data :

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