# Latest Results of ILC High-Gradient R&D 9-cell Cavities at JLAB*

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*Abstract*

It has been over a year since JLAB started processing and testing ILC 9-cell cavities in the frame work of ILC high-gradient cavity R&D, aiming at the goal of a 35 MV/m gradient at a $Q_0$ of 1E10 with a yield of 90%. The necessary cavity processing steps include field flatness tuning, electropolishing (EP), hydrogen out-gassing under vacuum, high-pressure water rinsing, clean room assembly, and low temperature bake. These are followed by RF test at 2 Kelvin. Ultrasonic cleaning with Micro-90, an effective post-EP rinsing recipe discovered at JLAB, is routinely used. Seven industry manufactured 9-cell TESLA-shape cavities are processed and tested repeatedly. So far, 33 EP cycles are accumulated, corresponding to more than 65 hours of active EP time. An emphasis put on RF testing is to discern cavity quench characteristics, including its nature and its location. Often times, the cavity performance is limited by thermal-magnetic quench instead of field emission. The quench field in some cavities is lower than 20 MV/m and remains unchanged despite repeated EP, implying material and/or fabrication defects. The quench field in some other cavities is high but changes unpredictably after repeated EP, suggesting processing induced defects. Based on our experience and results, several areas are identified where improvement is needed to improve cavity performance as well as yield.

## INTRODUCTION

35 MV/m is the goal gradient chosen by the ILC for vertical test acceptance of a 9-cell cavity. The number of 9-cell cavities needed by the ILC is about 17,000. This necessitates industrial fabrication and processing of these cavities. A crucial step toward industrialization is to achieve the goal gradient reliably in the lab environments, which is yet to be demonstrated. A coordinated effort has been put forward by GDE to address this outstanding issue.

So far, the most credible high-gradient cavity processing method is electropolishing (EP). It appears, however, that the gradient of electropolished cavities varies widely, despite there is no known fundamental reasons for this to be the case. To address the challenge of achieving 35 MV/m reliably, JLAB became involved in the high-gradient cavity R&D, in collaboration with FNAL.

Since the commissioning of the EP facility in early 2006, JLAB has been processing and testing ILC 9-cell cavities, fabricated by the industry and purchased by FNAL. Besides the EP facility, many other JLAB's cavity facilities are needed to fully process and test a 9-cell cavity. These include the tuning machine for field flatness and frequency tuning, the vacuum furnace for out-gassing hydrogen, the ultrasonic tank and high-pressure water rinser for cavity cleaning, the class-10 area for clean room assembly, the oil-free pump stand for cavity evacuation, the radiation-shielded 2 Kelvin Dewar and the RF system for cavity testing. Upgrading some of these facilities has been and will be an on-going process to address the demanding need of ILC high-gradient R&D.

## EP FACILITY

The JLAB EP facility (Fig. 1), originally established for processing 805 MHz SNS cavities, has been adapted for processing ILC 9-cell 1300 MHz cavities. The detailed information about design features of the facility can be found in Ref. [1]. The EP system operation is fully automated with PLC and a Labview program. EP processing is done horizontally while rotating the cavity at 1 RPM. The electrolyte (HF(49%):$H_2SO_4$(96%)=1:9(v:v)) is filled into the cavity at a rate of typically 10 liter per minute and is returned (through overflowing at end groups) back into the acid sump where cooling is provided by an external heat exchanger. The voltage across the aluminum cathode and

Figure 1: EP facility with an ILC 9-cell cavity installed in the main EP cabinet.

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the cavity is typically in the range of 14-17 V, sometimes varied during the process for cell temperature control.

The material removal has a fairly uniform distribution from the iris region to the equator region, as measured with a ultrasonic thickness gauge. The typical averaged removal rate is 0.4 $\mu$m/min. Since July 2006, 33 EP runs have been done. The total voltage-on time exceeds 65 hours.

## 9-CELL CAVITY PROCESSING PROCEDURE

Guided by the recommendations of the ILC S0/S1 task force, the ILC 9-cell cavity processing procedure [2] consists of the following steps for an as-built cavity,

1. Field flatness tuning.
2. Bulk EP (nominal 150 $\mu$m).
3. Ultrasonic cleaning (1 hour).
4. Hydrogen out-gassing (600 °C 10 hours).
5. Field flatness tuning.
6. Light EP (nominal 20 $\mu$m).
7. Ultrasonic cleaning (1 hour).
8. HPR (12 hours).
9. Class-10 area drying (8 hours).
10. Class-10 area assembly.
11. Second HPR (12 hours).
12. Final class-10 area assembly.
13. Pump down and leak check.
14. Low temperature bake (120 °C 48 hours).
15. RF test at 2 Kelvin.

After the completion of the first cycle of processing and testing, the same cavity goes through step 6-15 repeatedly for 3 times. Some ILC cavities previously evaluated at other labs first have a base-line test at JLAB after high-pressure water rinsed only. The same cavity then loops through step 6-15 three times.

60 Gallons of electrolyte is required for the JLAB EP processing. Depending on the accumulated use, the aging electrolyte is either discarded or re-used by adding additional HF.

It is worth mentioning that the ultrasonic cleaning with a solution of detergent, micro-90, and DI water is routinely used following the EP process. This seemingly simple procedure has shown encouraging initial results in reducing field emission [3].

## 9-CELL CAVITY RESULTS

Besides cavities S35 (for initial commissioning of the JLAB EP system) and C22 (for HTS of Fermilab), three ACCEL-built cavities A6, A7, A8, four AES-built cavities AES1, AES2, AES3, AES4 are repeatedly processed and tested (all purchased by FNAL). Recently, we have also received a low-loss shape cavity, ICHIRO#5, from KEK.

Six cavities (A6, A7, AES1, AES2, AES3, AES4) are received without prior chemistry. A8 and ICHIRO#5 are received after processing and test at Cornell University and KEK, respectively. Table 1 summarizes the processing steps and testing results for all cavities. The maximum gradients achieved during these tests are also shown in a bargraph in Fig. 2. The first test of cavity A8 (after HPR

Table 1: Summary of cavity processing and testing

| Cavity | Test | Processing | $E_{acc}^{max}$ [MV/m] | Limit |
|---|---|---|---|---|
| A6 | 1 | EP 187 $\mu$m | 19.4 | Q-slope |
| A6 | 2 | + EP 26 $\mu$m | 29.1 | Quench |
| A6 | 3 | + EP 26 $\mu$m | 25.0 | Quench |
| A6 | 4 | + EP 26 $\mu$m | 37.9 | FE |
| A7 | 1 | EP 172 $\mu$m | 29.3 | Quench |
| A7 | 2 | + EP 26 $\mu$m | 41.7 | Quench |
| A7 | 3 | + EP 26 $\mu$m | 30.5 | Quench |
| A7 | 4 | + EP 27 $\mu$m | 31.9 | Quench |
| A8 | 1 | HPR only | 22.1 | Q-slope |
| A8 | 2 | + EP 23 $\mu$m | 20.0 | FE |
| A8 | 3 | + EP 23 $\mu$m | 6.0 | FE |
| AES1 | 1 | EP 213 $\mu$m | 17.5 | Quench |
| AES1 | 2 | + EP 23 $\mu$m | 18.1 | Quench |
| AES1 | 3 | + EP 16 $\mu$m | 17.0 | Quench |
| AES1 | 4 | + EP 17 $\mu$m | 16.2 | Quench |
| AES2 | 1 | EP 164 $\mu$m | 19.6 | Quench |
| AES2 | 2 | + EP 26 $\mu$m | 18.0 | Quench |
| AES3 | 1 | EP 177 $\mu$m | 18.7 | Quench |
| AES3 | 2 | + EP 23 $\mu$m | 17.6 | Quench |
| AES3 | 3 | (re-test) | 17.4 | Quench |
| AES3 | 4 | HPR only | 7.0 | Q-drop |
| AES4 | 1 | EP 221 $\mu$m | 27.8 | FE |
| AES4 | 2 | + EP 36 $\mu$m | 25.5 | Cable |
| AES4 | 3 | + EP 20 $\mu$m | 19.5 | FE |
| AES4 | 4 | + EP 23 $\mu$m | 21.5 | FE |
| ICHIRO#5 | 1 | HPR only | | |

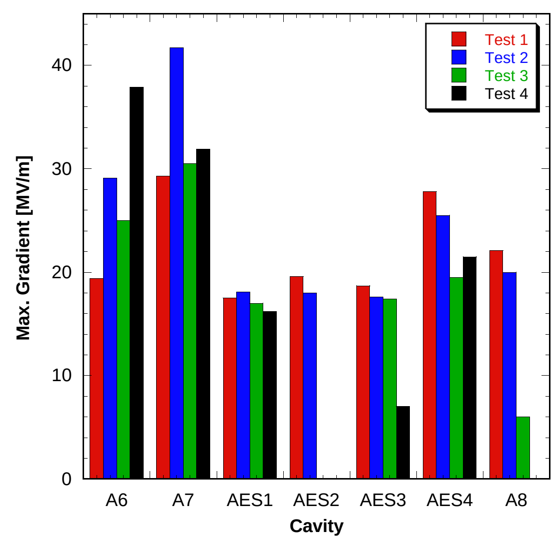



Figure 2: Maximum gradients achieved by 9-cell cavities.

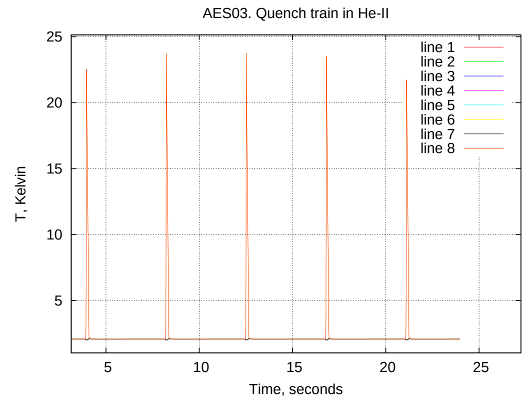
only at JLAB) shows a Q-slope, in agreement with the last result at Cornell. The Q-slope is attributed to a parameter change during the last EP done at Cornell [4]. The 4th test result of AES3 has a sharp Q-drop up to 7 MV/m. Two rings of niobium oxide are observable inside the beam tube of the field probe side. These are caused by the 12-hour bombardment from two HPR water jets (no wand movement due to HPR system malfunctioning).

## IDENTIFYING QUENCH SOURCES

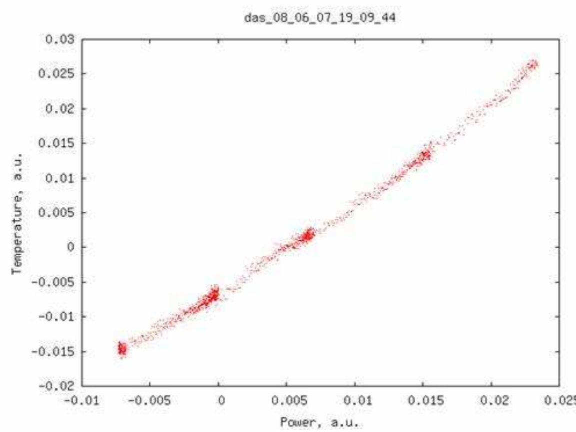
Among the 34 9-cell cavity tests at JLAB, 58% are limited by quench. It appears that one can separate the quench behaviors into two groups.

The quench field in the first group (such as A6 and A7) is in the high gradient range of 25 - 42 MV/m. The quench field in the same cavity can have large variations, either upward or downward, when repeated EP is applied. One hypothesis is that the final niobium surface has non-uniform physical properties, originated from variable EP conditions. It is known from experience and measurements [5] that the temperature and acid movement velocity both have strong effects on EP. In the existing horizontal EP method, there are intrinsic variations in the local temperature and acid movement velocity. Future 9-cell cavity processing and testing at JLAB are expected to address these issues, with the assistance of added 9-cell process diagnostics and dedicated single-cell cavity studies.

The quench field in the other group (such as AES1 and AES3) is in the gradient range of 15 - 20 MV/m. It remains unchanged despite repeated EP. Pass-band measurements of AES1 reveal consistently the quench is originated from the same cell pair of cell #3 and 7 (cell number counted from the field probe side) during the 3 tests, each following additional surface removal of 20 $\mu$m. Similar behavior is observed in AES3, in which case the source of quench resides in cell pair of cell #4 and 6. Additional RF tests were performed with thermometers attached to AES3 at the equator, 4 each on cell #4 and 6, 90 degree apart, starting at the overlap of the equator beam weld. At the quench gradient, two thermometers on cell 6 showed temperature spikes, synchronized with the cyclic field collapsing events (Fig. 3(a)). Other thermometers, including the one at the overlap of equator weld of the cell 6, remained silent. Gradient scanning just below the quench field clearly shows non-quadratic heating in the region surrounding the thermometer approximately 180 ° away from the equator overlap (Fig. 3(b)). It is concluded from these data that the source of quench in AES3 is near the equator weld of cell 6 and the overlap of its equator weld is not responsible. We expect to pinpoint the location of the defect during a subsequent RF test with 16 thermometers attached to the suspected region in cell 6. This is to be followed by visual inspection of the defect with a long-distance microscope.




(a)



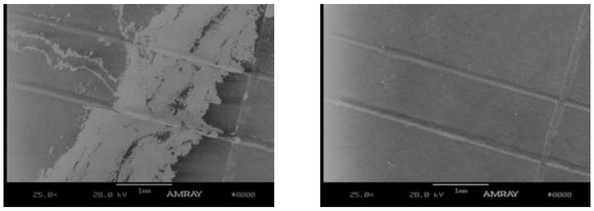

(b)

Figure 3: (a) Cyclic temperature spikes corresponding to self-pulsed quench events. (b) Non-quadratic temperature rise near the defect just below the quench field.

## IDENTIFYING FIELD EMISSION SOURCES

The post-EP ultrasonic cleaning with micro-90 has shown initial effectiveness in reducing field emission. However, there are still some 9-cell RF tests (18% out of the 34 tests) limited by field emission. Identification of the sources of field emission and improving solutions remain relevant for reliably achieving high gradients.

We started the studies of the initial surface contamination and changes made by the post-EP cleaning procedures. A niobium coupon, loaded in the input coupler port of a 9-cell cavity, is electropolished together with the cavity. The coupon is then analyzed with SEM, EDX and SFEM at JLAB's Surface Science Lab. Analysis is repeated after the coupon is ultrasonically cleaned with micro-90 and HPR. Fig. 4 gives a preliminary result showing the change



(a) (b)

Figure 4: A niobium surface electropolished together with a 9-cell cavity. Before (a) and after (b) ultrasonic cleaning with micro-90.

made by ultrasonic cleaning with micro-90 on a niobium surface electropolished together with a 9-cell cavity. EDX shows no foreign element except niobium and oxygen in both cases. No sulfur particle is observed on electropolished niobium surfaces so far.

Electropolishing a single-cell cavity with the same 9-cell EP system produces similar surface conditions and we plan to perform field emission studies with single cell cavities in the near future.

## SUMMARY

JLAB's EP and other SRF facilities are successfully used for processing and testing of ILC 9-cell niobium cavities. At JLAB, the ILC goal gradient of 35 MV/m was achieved first in the America region. The first four ILC 9-cell cavities fabricated by US industry were also processed and tested at JLAB.

33 EP cycles have been carried out, corresponding to 67 hours of voltage-on time. 34 RF tests of 9-cell cavities have been accumulated, contributing to more than 75% of the 9-cell data in the America region. Fig. 5-11 give the summary of the 9-cell cavity results.

Post-EP ultrasonic cleaning with micro-90 has shown initial success in reducing field emission. Less than 20% of the tests at JLAB are limited by field emission. By keeping field emission out of the picture and with additional help from the pass-band measurements and selective thermometry, it is now possible to distinguish the quench behavior due to process variability from that due to material/fabrication. JLAB is constructing two sets of 1-cell thermometry boards suitable for T-mapping of the TTF cavity shape. Combined with the existing JLAB single-cell cavity T-map system, these boards will be able to efficiently determine defect locations. Optical inspection of the defective region with a long-distance microscope will follow.

Achieving the ILC goal gradient of 35 MV/m at a $Q_0$ of $10^{10}$ with an yield of 90% remains a challenge. However, it is still premature to draw a conclusion about the processing yield, because only 2 as-built cavities from the qualified vendor haven been processed and tested following the procedure at JLAB. (although both achieved ILC goal gradient.) Other cavities were used for vendor qualification or to verify processes developed at other labs. We expect that more cavities from the qualified vendor will be processed and tested at JLAB in the future.

One can conclude from these latest data that further improvement in cavity fabrication is necessary. We have been actively involved in providing feedback information to the US industries in the spirit of helping them to become qualified cavity vendors. We expect to process and test new cavities from the US industries with improved fabrication procedures.

## ACKNOWLEDGMENT

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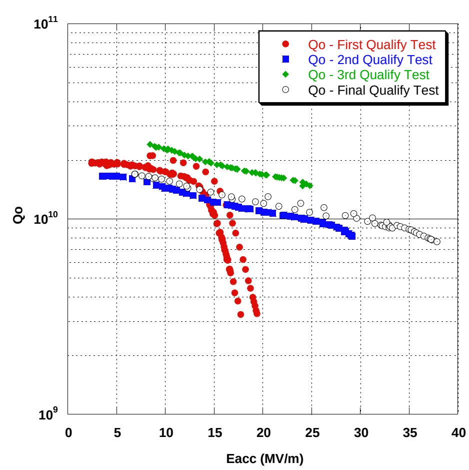


Figure 5: A6 results.

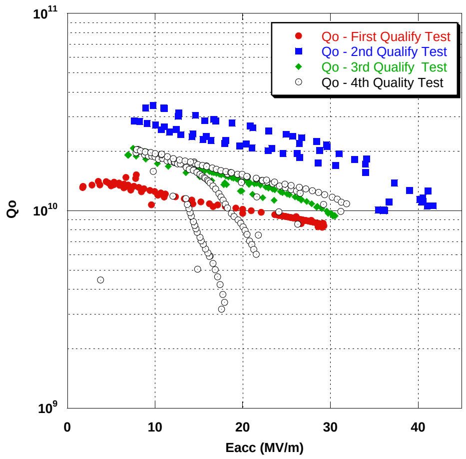


Figure 6: A7 results. (Note: second test data at 1.6 K.)

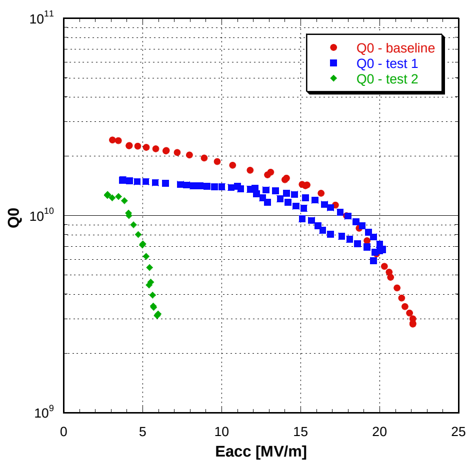


Figure 7: A8 results.

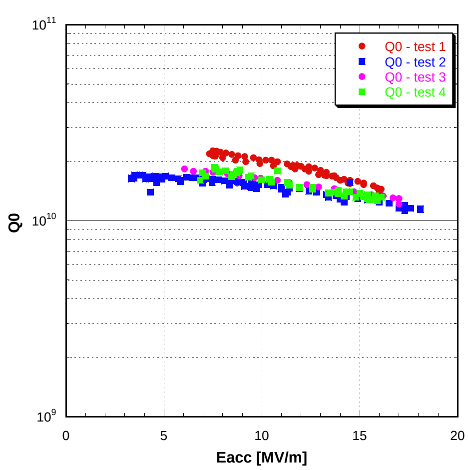


Figure 8: AES1 results.

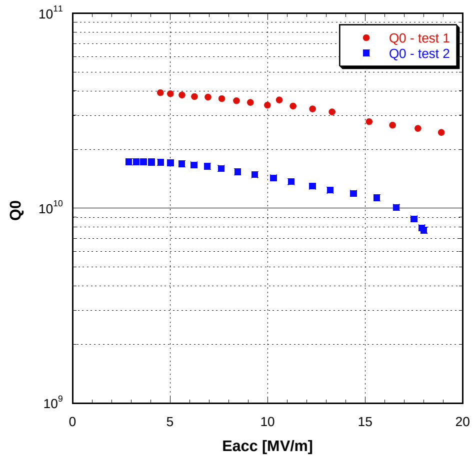


Figure 9: AES2 results.

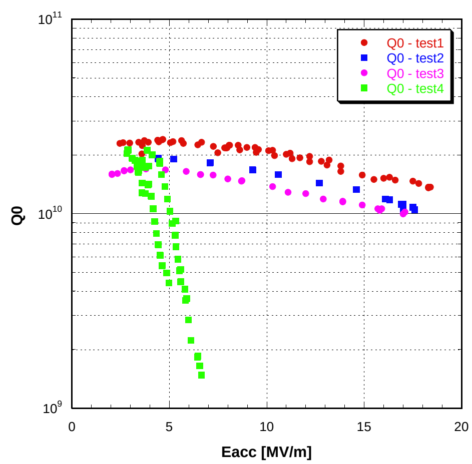


Figure 10: AES3 results.

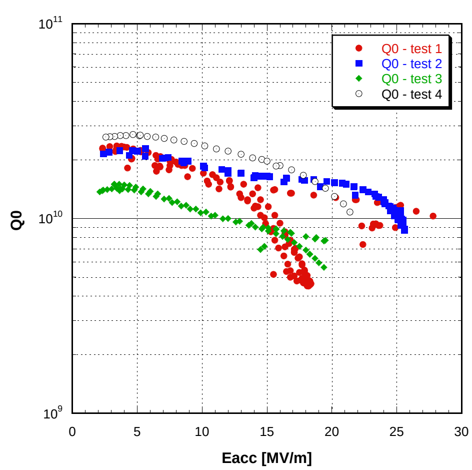


Figure 11: AES4 results.