PROGRESS OF ILC HIGH GRADIENT SRF CAVITY R&D AT JEFFERSON LAB*

R.L. Geng#, J. Dai, G. Eremeev, A. Palczewski, Newport News, VA 23606, U.S.A.

Abstract

Latest progress of ILC high gradient superconducting RF (SRF) cavity R&D at Jefferson Lab is presented. 9 out of 10 real 9-cell cavities, manufactured by an experienced industrial vendor, reached an accelerating gradient of more than 38 MV/m at an unloaded quality factor of more than 8E9. New understandings of quench limitation in 9-cell cavities are obtained through instrumented studies of cavities at cryogenic temperatures. Our data have shown that present limit reached in 9-cell cavities is predominantly due to localized defects, suggesting that the fundamental material limit of niobium is not yet reached in 9-cell cavities and further gradient improvement is still possible. Possible solutions to pushing toward 50 MV/m SRF cavities will be described.

INTRODUCTION

The accelerating gradient choice has a significant impact to the energy reach and the project cost for the International Linear Collider (ILC). The baseline ILC design requires a cavity accelerating gradient of 31.5 MV/m in average with an allowable spread of < ±20% (TESLA-shape cavity) to achieve a center-of-mass energy of 500 GeV with two 11-km long main linacs. The vertical test acceptance specification is 35 MV/m at Q_0 8E9, with an allowable gradient spread of < ±20% [1]. The ILC cavity gradient R&D program is a global effort with major contributions from DESY, JLab, FNAL, KEK and Cornell [2]. A major focus is to improve the gradient yield. In the mean time, a broader range of SRF cavity R&D topics are being addressed in support of ILC, such as alternative cavity shapes, large-grain niobium material, mechanical polishing for bulk removal and seamless cavity fabrication. The alternatives are relevant to the ILC gradient goal in terms of reaching higher ultimate gradient, improving gradient reproducibility or reaching the same gradient at potentially lower cost.

Jefferson Lab has been involved in ILC high-gradient SRF cavity gradient R&D since 2006. Up to now, more than 50 9-cell cavities have been processed and/or tested at JLab. More than 110 ILC cavity EP cycles have been accumulated, corresponding to more than 330 hours of active EP time. More than 150 cavity RF tests at cryogenic temperatures have been completed including the cavity qualification tests and instrumented studies for understanding of quench limit and field emission limit.

Through a closed-loop effort, the JLab high-gradient cavity processing and handling procedures have been established, standardized, and routinely applied. This led to repeatable processing and resulted in reproducible high gradient and high Q_0 results. As an example, nine out of ten 9-cell cavities manufactured by ACCEL/RI achieved a gradient of more than 38 MV/m at Q0 of more than 8E9 up to a second-pass processing. Further more, four out of six 9-cell second production batch cavities manufactured by AES achieved a gradient in the range of 36-41 MV/m, validating the vendor to become the first "ILC certified" manufacturer in the US industry.

The JLab cavity gradient R&D effort for ILC also addresses the understanding of the gradient limitation through instrumented cavity RF testing at cryogenic temperatures in association with non-destruction inspection of the cavity RF surfaces. In addition, focused surface studies of niobium samples electropolished together with real cavities were studied, revealing that sulfur-bearing niobium oxide granules to be an intrinsic type of field emitters [3]. On the quench limit studies, a 2-cell thermometry system (for studying heating in equator regions of any two cells of a 9-cell cavity) was initially built at JLab, based on the experience with the single-cell cavity thermometry system [4]. In parallel, a long-distance microscope based high-resolution optical cavity inspection apparatus was built for studying 9-cell cavities [5]. Based on a dozen 9-cell cavities built by experienced as well as "new" vendors, the following conclusions were made on the nature of quench limit in 9-cell cavities [6][7]:

- Only one outstanding defect in one cell limits the entire cavity while other cells already reaching a high gradient in the range of 28-44 MV/m.
- Quench-causing defects (type-I) for gradient limit in the range of 15-25 MV/m are often geometric circular irregularities with a diameter of 0.2-1 mm inside or near the equator electron-beam welding seam.
- Quench-causing defects (type-II) for gradient limit in the range of > 25 MV/m are often ***not*** correlated with observable features.
- Type-I defects are originated from the fabrication process and repeated surface processing has little effect in removing these defects.

Based on these findings, our quench limit studies continued to improve. For the rapid determination of quench location in 9-cell cavity testing, the Cornell OST's are adopted [8]. High-resolution local thermometry apparatus is being developed for studies of detailed pre-heating behaviors of previously identified defects [9]. The KEK replica technique has been adopted for characterization of the topology of defects [10].

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
# geng@jlab.org

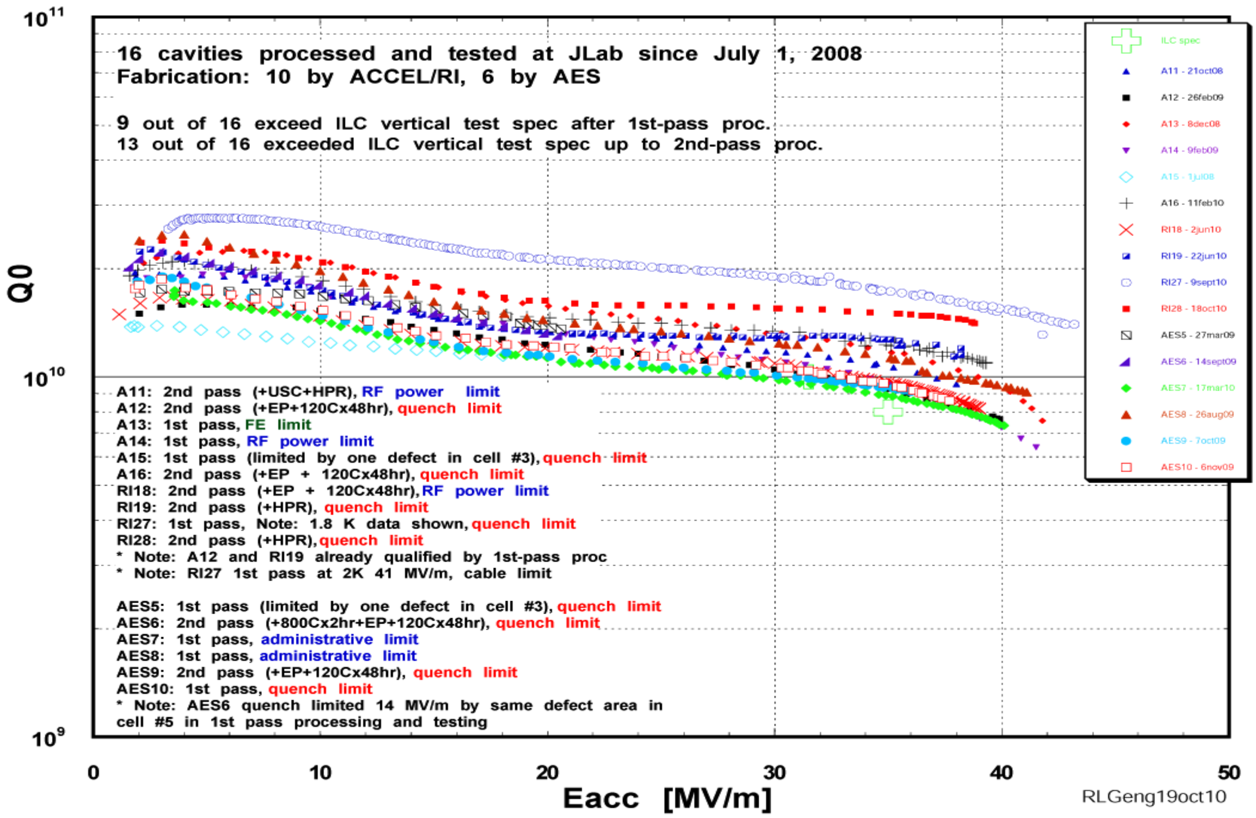

Figure 1: $Q(E_{acc})$ curves of all baseline 9-cell cavities processed and tested, without bias, since July 2008. Ten cavities are manufactured by ACCEL/RI; six by AES. These cavities are processed up to a second pass. See text for explanation.

DEMONSTRATION OF 90% GARDIENT YIELD AT 38 MV/m

By using the JLab standard ILC cavity processing and handling procedures [11], ILC baseline design 9-cell cavities are processed and tested in a "production" fashion at JLab. Fig. 1 shows the $Q(E_{acc})$ curves of 16 cavities (10 manufactured by ACCEL/RI and 6 by AES) processed without bias in the past three years (up to a second-pass processing). The second-pass processing path is decided by the gradient limited of the first-pass processing. It includes re-EP and re-HPR. For cavities passing the ILC vertical test specification already at first-pass, no re-processing is followed. This processing protocol allows assessing the gradient yield in a fashion relevant to the so-call "production yield" that is needed for the cost estimation of the ultimate ILC cavity mass production.

From the results of these 16 9-cell cavities, 13 cavities pass the ILC vertical test specification, corresponding to a production yield of 81% at 35 MV/m. All cavities passing the gradient specification meet the Q_0 specification. Four out of the six 9-cell cavities of the second AES production batch (AES5-AES10) achieved a gradient in the range of 36-41 MV/m at a Q_0 of more than 8E9 at 35 MV/m. This result validated AES as the first "ILC certified" industrial vendor in the US for ILC cavity manufacture [12].

Because a vendor accumulates more experience as more cavities are manufactured, the cavity gradient yield should show vendor dependence. Fig. 2 illustrates the first-pass and second-pass gradient yield of 10 9-cell cavities manufactured by ACCEL/RI, a vendor with experience of hundreds of 9-cell cavity fabrication. A 90% yield at 38 MV/m is demonstrated.

This result suggests: (1) the ILC goal of 90% production yield at 35 MV/m is reachable; (2) With practicing, new vendors can be expected to achieve the same level of high production yield.

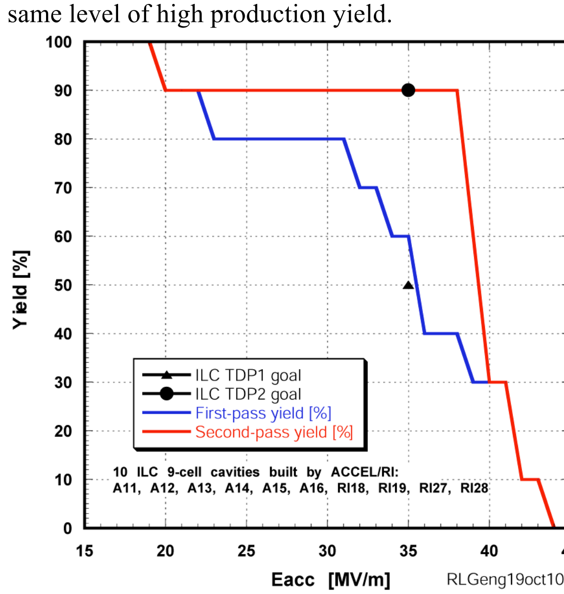

Figure 2: First-pass and second-pass gradient yield based on 10 9-cell ILC baseline cavities manufactured by ACCEL/RI and processed and tested at JLab.

NATURE OF QUENCH LIMIT

In order to further study the nature of identified quench-causing ***local*** defects, we re-test selected cavities with high-resolution thermometry. An example is given in Fig. 3 [9]. The "dual mode excitation" technique has been developed. An example is given in Fig. 4 [13]. The data show that the breakdown regime is neither pure thermal nor pure magneto. Optical inspection reveals a geometrical defect at the quench location. Clearly this is an example of magneto-thermal breakdown induced by a geometric defect. In fact, so far pure thermal or pure magneto breakdown regime has been rarely measured.

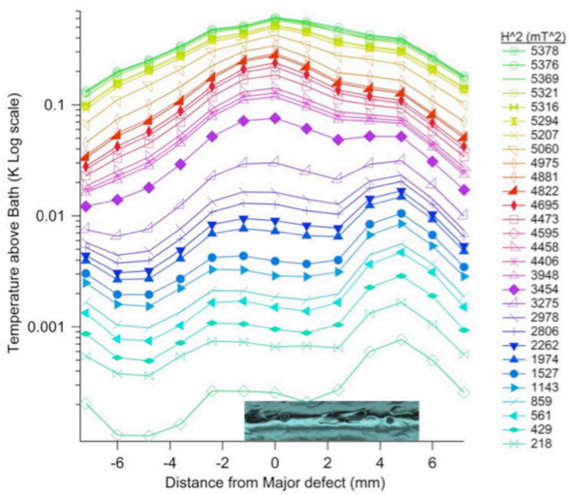

Figure 3: Temperatures measured at defect location of 9-cell cavity NR1. The pre-heating shows clear distinction of two defects 3.8 mm apart.

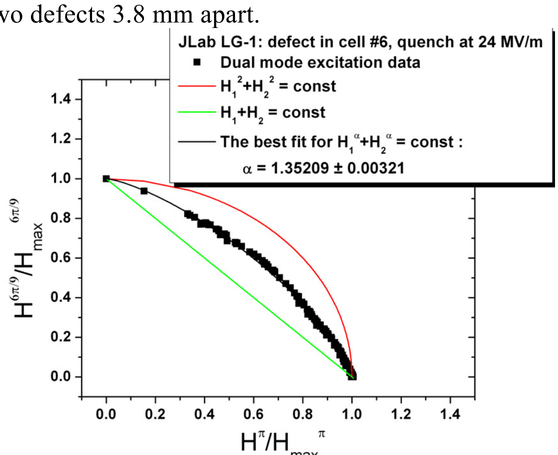

Figure 4: Proof of magneto-thermal breakdown regime. Dual mode excitation measurements are done with 9-cell JLAB LG#1 (quench at 24 MV/m.) Data fall between pure magneto breakdown regime (green straight line) and pure thermal breakdown regime (red circular arc).

CONCLUSION AND OUTLOOK

A standard ILC cavity processing and handling procedure has been established at JLab. An example of 90% yield at 38 MV/m has been established up to a second pass processing, suggesting the ILC gradient goal is reachable. Due to the fact that (1) most known quench limit is caused by highly localized defects and (2) known quench limit is rarely pure magneto, we believe the fundamental material limit of niobium is still not reached in 9-cell cavities. Reducing geometric defects and improving the thermal conductivity (near 2K) of the cavity wall material are the two most promising solutions to pushing toward 50 MV/m SRF cavities.

ACKNOWLEDGEMENTS

Many colleagues at JLab contributed to the work reported here, especially the following people: Tiffany Bass, Andrew Burrill, Jim Follkie, Danny Forehand, Tom Goodman, Pete Kushnick, Kurt Macha, Michael Morrone, Roland Overton, and Tony Reilly.

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