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

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Abstract

We report on the progress of ILC high gradient cavity R&D at Jefferson Lab since the Berlin conference. The optimal cavity processing recipe has been developed and applied for reproducible high gradient and high Q_0 results in real 9-cell cavities. An example of 90% gradient yield at >35 MV/m is demonstrated based on 10 cavities built by an experienced vendor. JLab qualified 9-cell cavities are sent back to FNAL, contributing to the first ILC cryomodule CM2 in the US. Advanced quench studies of 9-cell cavities are enhanced by new instrumentations. Besides the main work with the ILC baseline cavities, we have also processed and tested ILC alternate cavities including 9-cell large-grain niobium cavities and 9-cell low-loss shape cavities in collaboration with Peking University, KEK, and IHEP. A 9-cell seamless cavity from DESY has completed EP processing and RF testing. To date, more than 50 9-cell cavities have been processed and/or tested at JLab under the American Regional Team program in support of ILC. More than 110 ILC cavity EP cycles have been accumulated, corresponding to more than 330 hours of active EP time. More than 150 ILC cavity RF tests at cryogenic temperatures have been completed including cavity qualification tests and instrumented studies for understanding of quench limit.

INTRODUCTION

The accelerating gradient choice has a significant impact to 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. In this paper, an overview of high gradient SRF R&D at JLab will be given for baseline ILC cavities, alternative cavities as well as focused R&D with 1-cell cavities. JLab collaborates with FNAL, KEK, Cornell, DESY, PKU and IHEP and cooperates with the cavity fabrication industry in many activities reported herein.

The high gradient cavity processing and handling procedures have been established, standardized, and routinely applied. The repeatable processing has shown to result in reproducible high gradient and high Q_0 results. 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. 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 cavity quench studies are further enhanced by adopting the Cornell OST's and the KEK replica technique, in addition to the existing JLab fixed thermometry system and JLab high-resolution optical inspection machine. Advanced quench studies through dual-mode excitation and high-resolution local thermometry have resulted in new insight into the nature of cavity quench behaviors at low as well as at high surface magnetic fields. First results have been obtained in studies of a 1-cell cavity with controlled geometrical defects, elucidating the initiation of phase transition due to local magnetic field enhancement and the interplay with the heat generation and conduction. We have also EP processed and tested alternative cavities, including low-loss (ICHIRO) shape 9-cell cavities, large-grain niobium 9-cell cavities and seamless 9-cell cavities, in collaboration with KEK, PKU and DESY.

Up to now, more than 50 9-cell cavities have been processed and/or tested at JLab under the America Regional Team program in support of ILC. More than 110 ILC cavity EP cycles have been accumulated, corresponding to more than 330 hours of active EP time. More than 150 ILC cavity RF tests at cryogenic temperatures have been completed including the cavity qualification tests and instrumented studies for the understanding of quench limit.

BASELINE CAVITY RESULTS

Standard Cavity Processing and Handling Procedure

The standard procedures of ILC high gradient cavity processing and handling are described in Ref. [3]. The procedure includes optimized electropolishing, streamlined post-EP cleaning, updated vacuum furnace

* Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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out-gassing, no-touch bead-pull tuning and slow pumping down for cavity evacuation. The procedure has been shown to be repeatable with reproducible high gradient high Q_0 cavity results. It has been shown that this procedure is transferable through training and practicing. The procedure has been verified or adopted to some extent at other facilities. It is the basis of the final surface processing procedure for the 7-cell cavity of the CEBAF 12 GeV upgrade project.

Validation of the First US Industrial Vendor for ILC Cavity Manufacture

All 9-cell cavities of the first and second AES production batch were processed and tested at JLab under collaboration between JLab and FNAL. Four out of the six 9-cell cavities of the second AES production batch achieved a gradient in the range of 36-41 MV/m at a Q_0 of more than 8E9 at 35 MV/m [4]. Fig. 1 shows the $Q(E_{acc})$ curves of these cavities (AES5-AES10). This result validated AES as the first "ILC certified" industrial vendor in the US for ILC cavity manufacture.

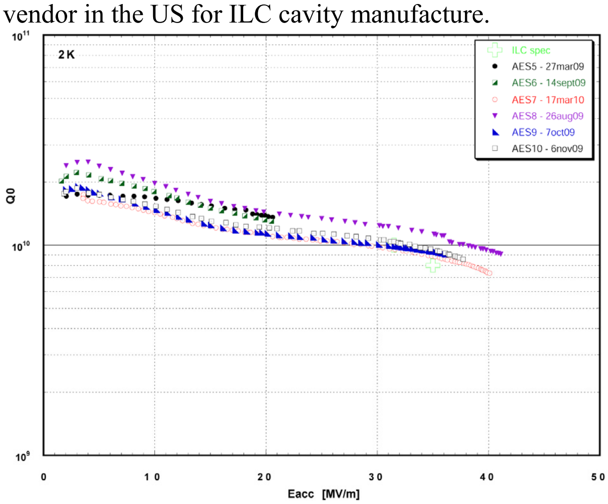

Figure 1: $Q(E_{acc})$ curves of the six 9-cell cavities of the second AES production batch.

An Example of 90% Gradient Yield at 38 MV/m

A large portion of ILC baseline 9-cell cavities processed and tested at JLab are manufactured at ACCEL/RI. Together with the second AES production cavities mentioned in previous section, 16 9-cell cavities have been processed and tested at JLab in last three years. Fig. 2 shows the $Q(E_{acc})$ curves of 16 cavities (10 manufactured by ACCEL/RI and 6 by AES) 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 is adopted as it 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. This protocol also allows desirable supply of qualified 9-cell cavities to the cryomodule program at FNAL.

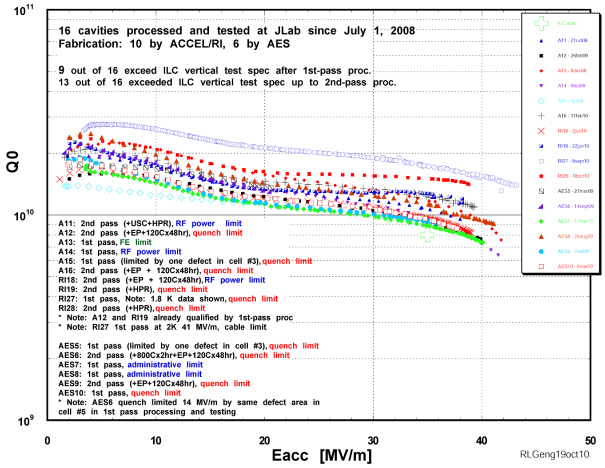

Figure 2: $Q(E_{acc})$ curves of all baseline 9-cell cavities processed and tested, without bias, since July 2008. Ten cavities are manufactured by ACCEL/RI; six by AES. These cavities are processed up to a second pass. See text for explanation.

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.

Because a vendor accumulates more experience as more cavities are manufactured, the cavity gradient yield should show vendor dependence. Fig. 3 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.

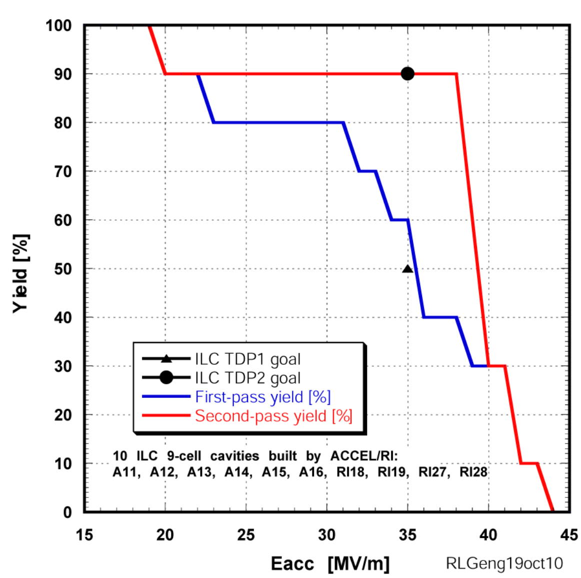

Figure 3: First-pass and second-pass gradient yield based on 10 9-cell ILC baseline cavities manufactured by ACCEL/RI and processed and tested at JLab.

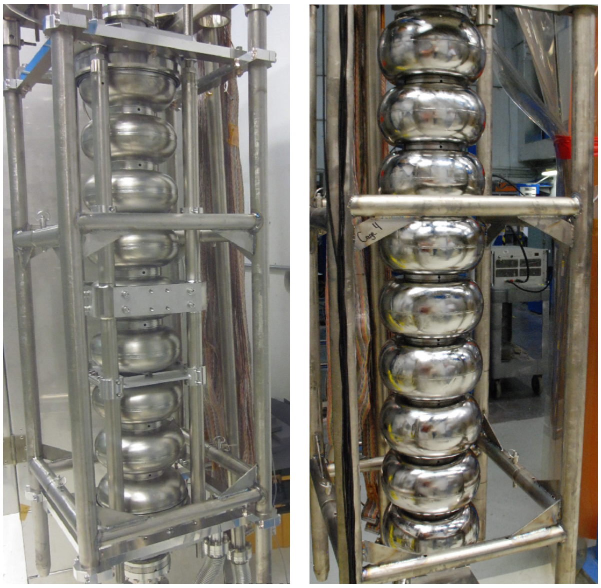

Figure 4: 9-cell cavity testing at JLab under cavity exchange program for ILC cavity R&D. Left: cavity MHI8 from KEK; Right: cavity IHEP-01 from IHEP.

Cavity Exchange for Cross-Checking Facilities

The ILC cavity gradient R&D is a globally coordinated effort. An important component of the effort is to exchange cavities for cross-checking cavity processing facilities. In the past, cavity exchange within America region between JLab and other labs (FNAL and Cornell) resulted in valuable feedback and increased confidence of the test results. More recently, cross-region cavity exchange efforts between JLab and Asia labs have started. Fig. 4 shows two cavities (MHI8 from KEK & IHEP-01 from IHEP) presently under processing and testing at JLab.

ADVANCED GRADIENT LIMIT STUDIES IN 9-CELL CAVITIES & BASIC QUENCH STUDIES WITH 1-CELL CAVITIES

The 9-cell cavity quench behaviors can be generally classified into two types [5]. Type-I quench limit occurs typically at a gradient > 25 MV/m. No observable feature at the quench site through optical inspection. Type-II quench limit occurs at a gradient in the range of 15-25 MV/m. It is often correlated with sub-mm sized geometrical defects. Both type-I and type-II quench limit occur locally in the region of the equator. It is important to understand these two types of quench behaviors for improving the gradient yield as well as for further pushing the achievable gradient in support of the 1 TeV ILC upgrade. Therefore, at JLab, significant effort has been recently devoted to the studies of quench limit in 9-cell cavities as well as to basic quench studies with 1-cell cavities.

We adopted the Cornell OST technology for rapid quench location detection in cavities of any shape. We adopted the KEK defect replica technology for detailed geometrical studies of identified quench-causing defect.

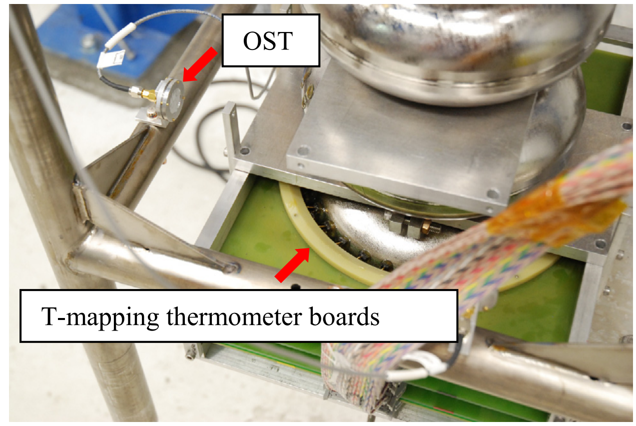

Figure 5: 9-cell cavity quench study instruments: Cornell OST sensors are set-up together with JLab temperature mapping thermometry boards for cross checking.

Instrumented 9-cell RF Testing

Instrumented 9-cell cavity quench studies have been started since 2008 [6]. A number of 9-cell cavities have been studied in conjunction with the high-resolution optical inspection [7]. This effort continues with a particular interest in understanding the type-I quench limit at high gradient regime [8][9]. By exiting two pass-band modes simultaneously, advanced quench studies allow differentiation of thermal quench from magneto-thermal quench [10]. These studies are facilitated greatly due to the assistance by the Cornell OST's [11]. Fig. 5 shows the set-up of an instrumented 9-cell RF test with JLab's temperature mapping system and Cornell OST's for cross checking.

Characterization of Quench-Causing Defect

We continue to perform optical inspection of the RF surface at predicted quench regions. The JLab high-resolution optical SRF cavity inspection machine is now upgraded [12]. Together with the Kyoto camera and the KEK replica technique recently transferred to JLab, improved characterization of defects and irregularities are carried out [13]. Fig. 6 shows an example of replica result.

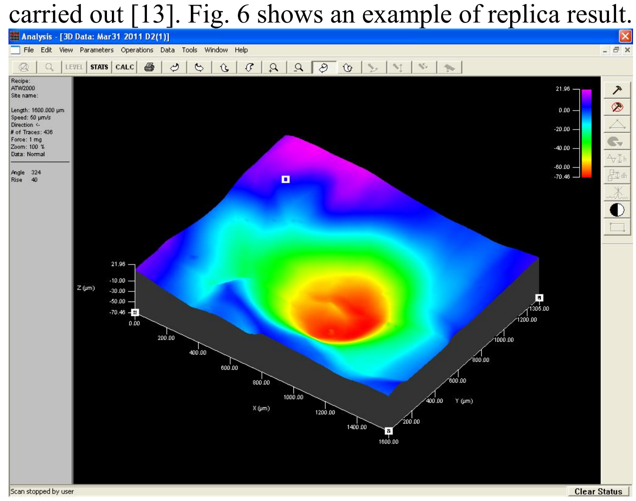

Figure 6: 3D contour of the replica of a defect near the equator weld of a 9-cell cavity.

Experimental Studies of Geometrical Defects using 1-Cell Cavity

To bridge the gap between the observed quench limits in 9-cell cavities caused by geometrical defects and the commonly adopted model of local magnetic field enhancement, a 1-cell CEBAF shape cavity (C1-3) was built with artificial pits created near the equator weld. RF testing was carried out with thermometry to elucidate the pre-heating behavior [14]. Fig. 7 shows an example of an artificial pit similar to the ones created in the 1-cell cavity C1-3. Clear pre-heating was measured at locations of artificial defects with a diameter of 400 μm and various depths. One 800 μm deep artificial pit caused the cavity to quench and is being studied in details with our new high-resolution local thermometry apparatus (see next section). Numerical calculations are also underway to investigate the interplay between the phase transition due to local magnetic field enhancement effect and the thermal feedback due to finite heat conduction across the wall thickness of the cavity.

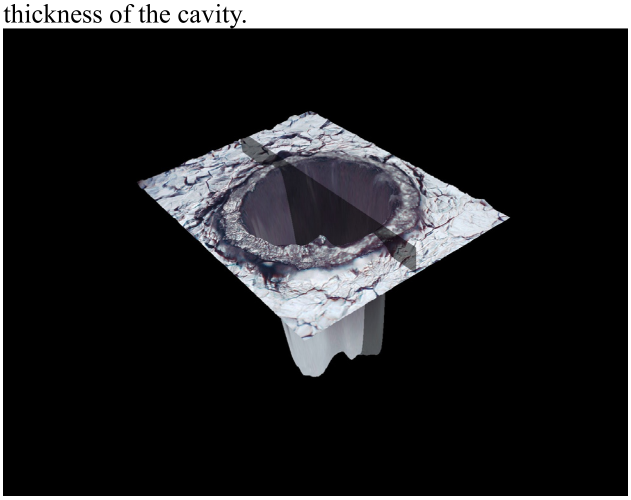

Figure 7: The image of an artificial pit similar to those created on the inner surface of a 1-cell cavity for advanced quench studies.

High-Resolution Local Thermometry for Advanced Quench Studies

The known quench limit, type-I or type-II, in 9-cell cavities tested in the past years at JLab is always initiated at a highly localized area. Detailed studies of pre-heating at quench location and the dynamics of the quench initiation and evolution processes are needed to understand the nature of the quench limit. Improved understanding would in turn help identify the key material parameters for improved gradient performance. For example, it is well known from earlier thermal quench studies that improving thermal conductivity of the cavity wall leads to improved quench limit due to thermal stabilization of normal conducting defects [15]. Most recently identified quench-causing defects are not correlated to normal conducting defects, rather they are either geometrical defects or perhaps some kind of defective local area with inferior superconducting properties.

As shown in the past, thermometry is a powerful tool for studying the loss mechanisms on the RF surface of a cavity. Thermometry studies of SRF cavities have been on-going for various research at JLab [16][6]. The existing thermometry systems at JLab are not well suited for detailed studies of identified highly localized defect because the spacing between thermometers is on the order of cm. Therefore, a high-resolution local thermometry system has been developed at JLab for advanced studies of defects identified by using our standard T-mapping system and OST system. Fig. 8 shows a photo of the system attached to the area of a 1-cell cavity with artificial pit created on the inner surface of the cavity near its equator electron beam weld joint. The new high-resolution local thermometry system has been successfully used to study a 1-cell cavity with artificial pits as well as a 9-cell cavity with natural defects in the equator electron beam weld, demonstrating a spatial resolution of about 1mm [17]. Further development of this system is continuing, aimed at studies of dynamical process of the quench process.

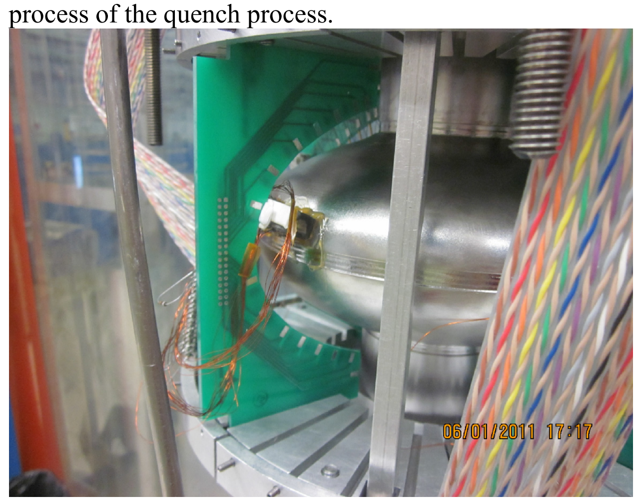

Figure 8: High-resolution local thermometry system developed at JLab for detailed studies of identified defects.

EP PROCESSING AND TESTING OF ALTERNATE DESIGN CAVITIES FOR 1 TEV ILC UPGRADE AND CAVITY COST REDUCTION

Besides the efforts mentioned above, we have been also engaged in developments of alternate cavities in collaboration with other institutions.

One effort is to advance low-loss shape cavities in collaboration with KEK [18]. The ICHIRO shape cavity has a reduced ratio of the peak surface magnetic field to the accelerating gradient. Therefore this cavity design has potential to reach higher gradient. It is one of the alternate cavity shape design for 1 TeV ILC upgrade. So far, two KEK 9-cell ICHIRO cavities (ICHIRO5, which does not have end group components; ICHIRO7, which has complete end group components) have been processed and tested at JLab. A third ICHIRO cavity (ICHIRO8) has been recently received for evaluation.

Another ILC alternate effort is to develop large-grain niobium cavity for cost reduction. A JLab large-grain cavity JLab LG#1 [19] has been EP processed and tested. In addition, another large-grain 9-cell cavity PKU2 have been EP processed and tested in collaboration with Peking University [20]. These two cavities both exhibited a high Q_0, as compared to the baseline fine-grain 9-cell cavities that are processed and tested according to the same procedure [21]. Seamless cavity technology has been also investigated to be a possible path for reducing ILC cavity cost because of the elimination of many electron beam welding joints. JLab has been pursuing this technology in collaboration with DESY [22]. Recently, a DESY 9-cell seamless niobium cavity was EP processed and tested at JLab, following the baseline testing after BCP processing. Further processing and testing will continue.

CONCLUSION AND OUTLOOK

ILC high gradient cavity work at JLab since 2006 has resulted in a standard ILC cavity processing and handling procedure. By using this procedure, an example of 90% yield at 38 MV/m has been established up to a second pass processing, based on 10 9-cell cavities manufactured by an experienced vendor and processed without bias at JLab. Processing and testing of the second production bath 9-cell cavities have resulted in validation of AES as the first US industrial vendor for ILC cavity fabrication. Instrumented cavity testing and optical inspection have improved understanding about quench limitation. Our baseline processing procedure has been used to process a variety of alternate ILC cavities. We expect an increased effort in alternate cavity development for higher gradient in support of 1 TeV ILC upgrade after the completion of ILC TDR publication in 2012.

ACKNOLEDGEMENTS

Many colleagues at JLab contributed to the work reported here, especially the following people: Tiffany Bass, Andrew Burrill, Gigi Ciovati, Jin Dai, Grigory Eremeev, Jim Follkie, Danny Forehand, Tom Goodman, Pete Kushnick, Kurt Macha, Michael Morrone, Roland Overton, Ari Palczewski, and Tony Reilly. We also want to thank Mark Champion and Camille Ginsburg of FNAL; Fumio Furuta, Hitoshi Hayano, Kenji Saito, Ken Watanabe and Kirk Yamamoto of KEK; Kexin Liu, Xiangyang Lu and Kui Zhao of Peking Univeristy; Jie Gao and Jiyuan Zhai of IHEP for fruitful collaborations.

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