

# OVERVIEW OF HIGH GRADIENT SRF R&D FOR ILC CAVITIES AT JEFFERSON LAB\*

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## Abstract

We report the progress on high gradient R&D of ILC cavities at Jefferson Lab (JLab) since the Beijing workshop. Routine 9-cell cavity electro polishing (EP) processing and RF testing has been enhanced with added surface mapping and T-mapping instrumentations. 12 *new* 9-cell cavities (10 of them are baseline fine-grain TESLA-shape cavities: 5 built by ACCEL/Research Instruments, 4 by AES and 1 by JLab; 2 of them are alternative cavities: 1 fine-grain ICHIRO-shape cavity built by KEK/Japan industry and 1 large-grain TESLA-shape cavity built by JLab) are EP processed and tested. 76 EP cycles are accumulated, corresponding to more than 200 hours of active EP time. Field emission (FE) and quench behaviors of electro polished 9-cell cavities are studied. EP process continues to be optimized, resulting in advanced procedures and hence improved cavity performance. Several 9-cell cavities reached 35 MV/m after the first light EP processing. FE-free performance has been demonstrated in 9-cell cavities in 35-40 MV/m range. 1-cell cavity studies explore new techniques for defect removal as well as advanced integrated cavity processing. Surface studies of niobium samples electro polished together with real cavities provide new insight into the nature of field emitters. Close cooperation with the US cavity fabrication industry has been undertaking with the successful achievement of 41 MV/m for the first time in a 9-cell ILC cavity built by AES. As the size of the data set grows, it is now possible to construct gradient yield curves, from which one can see that significant progress has been made in raising the high gradient yield.

## INTRODUCTION

The accelerating gradient choice has a significant impact to the project cost for the International Linear Collider (ILC). The current ILC design assumes a cavity accelerating gradient of 31.5 MV/m (baseline TESLA-shape) to achieve a center-of-mass energy of 500 GeV with two 11-km long main linacs. The vertical test acceptance gradient was decided to be 35 MV/m at the second ILC workshop in 2005 at Snowmass. Successful 9-cell cavity results of a DESY/KEK led collaboration provided the proof-of-existence of 35 MV/m by using EP surface processing and in-site low temperature bake treatment [1]. As shown clearly, EP is the necessary technology for reaching 35 MV/m in standard fine-grain

niobium cavities. Therefore it has been chosen as the base line processing method for ILC cavities.

Today, the ILC cavity gradient R&D program has become 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 and large-grain niobium material [3]. The alternatives are relevant to the ILC gradient goal in terms of reaching higher ultimate gradient (new shape cavities) or reaching the same gradient at potentially lower cost (large-grain material). In this paper, an overview of high gradient SRF R&D at JLab will be given for baseline ILC cavities, alternative shape cavities (ICHIRO cavities) as well as focused R&D with 1-cell cavities and niobium samples. JLab collaborates with FNAL and KEK and cooperates with the cavity fabrication industry in many activities reported here.

## ADVANCED 9-CELL CAVITY PROCESSING PROCEDURES

The main processing procedure at JLab is consistent with the base line ILC procedure (heavy EP + vacuum furnace out-gassing + light EP + cleaning + low temperature bake-out) with the unique post-EP ultrasonic cleaning in de-ionized water with detergent (Micro-90<sup>®</sup> was initially used. It has been replaced by Liquinox<sup>®</sup>. 2% volume concentration is needed for effectiveness [4][5]). The updated 9-cell cavity procedure is consisted of the following steps:

1. Rough field flatness tuning.
2. Ultrasonic cleaning.
3. Optional BCP (~10  $\mu\text{m}$  RF surface removal).
4. Heavy EP (~ 140  $\mu\text{m}$  removal at equator).
5. Ultrasonic cleaning.
6. Ethanol rinsing.
7. HPR (typical 4 hours).
8. Vacuum furnace heat treatment (600°C for 10 hours or 800°C for 2 hours).
9. Field flatness and frequency tuning.
10. Light EP (~ 25  $\mu\text{m}$  removal at equator).
11. Low pressure water rinsing.
12. Ultrasonic cleaning.
13. HPR (6 hours).
14. Class-10 area drying.
15. Class-10 assembly.
16. Second HPR (6 hours).
17. Final class-10 area assembly.
18. Slow pump down and leak check.
19. Low-temperature bake out (120°C 48 hours).
20. RF test at 2 Kelvin.

\* 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.

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Improvements in many areas have been made toward optimized EP processing. Initial acid mixing is made using a volume ratio of 1:10 (HF (49%):H<sub>2</sub>SO<sub>4</sub> (96%)). Nominal voltage across the cavity and cathode is 14-15 V. Acid supplying holes in the cathode face upward. The acid flows at a typical rate of 3-4 liter per minute. The optimal EP is done in the continuous current oscillation mode.[6][7]. More active temperature control is accomplished by steering the cooling water in the heat exchanging loop or sometimes by briefly turning off the voltage. The electrolyte circulation continues for another 30 minutes after the voltage is turned off. This improves removal of niobium oxide granules, which will be shown later to be a major type of field emitter intrinsic to electro polished niobium surfaces. The minimum purging N<sub>2</sub> gas flow reduces HF loss. Plugging openings around the acid sump prevents water (moisture) addition into acid and also reduces HF loss. Removal of residual water in the EP machine and in the acid sump before mixing new acid assures correct molar ratio of HF:H<sub>2</sub>O:H<sub>2</sub>SO<sub>4</sub>. Identification and removal of a major bug in the valve control logic resulted in significantly improved process reproducibility and eliminates completely the need of adding HF acid after the first use of a new batch of electrolyte. Reliable and reproducible EP processing is now possible for repeated use of the electrolyte, sometimes after over weeks of storage in the acid sump.

Ethanol rinsing and HPR after bulk EP and before vacuum furnace heat treatment improves S removal from niobium and avoids burning chemical residuals into the cavity surface. A method of bead-pull cavity without touching the RF surface eliminates possibility of surface damage due to accidental contact. Low pressure water rinsing and HOM can brushing following the light EP removes niobium oxide granules as well as S that are otherwise not effectively removed by HPR due to shielding effect.

The improved cleaning and assembly procedure, along with the advanced EP procedure, ensured a significant reduction in field emission and enabled the realization of > 35 MV/m in four 9-cell cavities (out of 5 manufactured by ACCEL) following the first light EP. One cavity (A12) demonstrated a remarkable gradient performance of 40 MV/m without detectable X-ray.

## NEW T-MAPPING AND OPTICAL INSPECTION INSTRUMENTS

A major development in ILC high gradient cavity R&D since last SRF workshop is the introduction of T-mapping and optical inspection instrumentations.

Thermometry studies were already started at Jefferson Lab two years ago in pursuit of understanding the quench behavior of an electro polished 9-cell cavity whose performance was limited below 20 MV/m and was insensitive to repeated EP processing [5]. Taking advantage of the existing hardware/software for a 1-cell cavity thermometry developed previously at JLab, two sets of thermometry boards were fabricated and have been routinely used for quench location determination in 9-cell

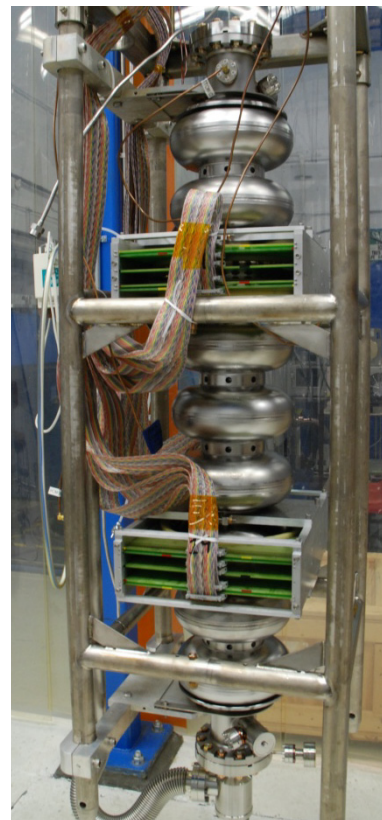


Figure 1: JLab T-mapping system mounted to a 9-cell cavity for determination of quench location and pre-cursor heating studies of the defect site.

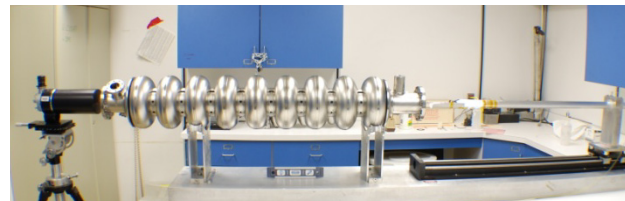


Figure 2: JLab long-distance-microscope based optical inspection apparatus.

cavities, [8]. Each board hosts 160 carbon resistors, fully covering the equator and the neighborhood area. This system (Fig. 1) not only captures quench events but also provides pre-cursor heating data at quench locations.

An optical inspection apparatus (Fig. 2) based on a long-distance-microscope and a mirror was developed at JLab [11]. It has been routinely used for inspecting regions of the quench location determined by the T-mapping system and imaging and documenting responsible defects. It has been also used for inspection of as-built as well as partially processed cavity surfaces, in an attempt to discern the role of material/fabrication in bring about the operating defects. The system has a spatial resolution of up to 3  $\mu\text{m}$ . It is possible to inspect the entire surface of a cavity by tilting the mirror. The cavity can be rotated automatically. A laser-based device is being implemented to allow precise projection of interior defect location to the cavity exterior surface. Our next step is to improve automation and add new analytical capabilities.

### NEW 9-CELL CAVITY RESULTS

#### Achievement of > 35 MV/m in 4 out of 5 Cavities Manufactured by ACCEL

The performance of 5 new cavities manufactured by ACCEL (A11, A12, A13, A14 and A15) is given in Fig. 3. Among these 5 cavities, 4 (A11, A12, A13, A14) reached a gradient of > 35 MV/m after the first light EP. A15 was limited at 19 MV/m by quench due to a defect near the equator weld of the cell #3. Note that A12 result shown in Fig. 3 is that obtained after a second light EP (for removal of HPR damage introduced during additional preparation after initial successful qualification).

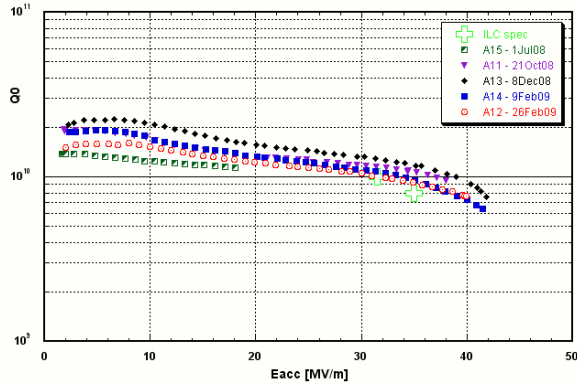


Figure 3: Performance of 5 new cavities manufactured by ACCEL and EP processed and tested since July 2008 at JLab. Error bars are not shown for clarity.

#### Achievement of first 41 MV/m in AES8 – a 9-cell Cavity Built by US Cavity Vendor AES

The performance of 4 new AES cavities (AES5, AES6, AES8 and AES9) is given in Fig. 4.

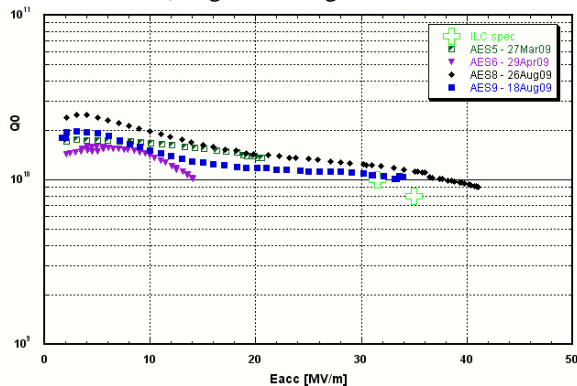


Figure 4: Performance of 4 new cavities manufactured by AES and EP processed and tested recently at JLab. Error bars are not shown for clarity.

These 4 cavities are among the new batch of 6 cavities manufactured by AES using their own EBW machine and improved techniques. These results are obtained after only one light EP. AES8 exceeds the ILC vertical test specification and reached a maximum gradient of 41 MV/m (administrative limit). AES9 reached a maximum gradient of 34 MV/m with a  $Q_0$  of  $> 1 \times 10^{10}$  limited by

quench. AES5 & 6 are limited by quench at < 21 MV/m, due to defects in cell #3 and #5, respectively. It should be noted that AES8 and AES9 were vacuum furnace treated at 800°C for 2 hours for hydrogen out-gassing, whereas AES5 and AES6 were treated at 600°C for 10 hours (a standard recipe in the past for 9-cell processing). AES8 was light BCP etched for a 10 µm removal from its inner surface which eliminated weld spatters and created a desirable starting surface before heavy EP processing.

#### Pushing Gradient in low-loss Shape Cavities

A low-loss shape cavity (ICHIRO#5) from KEK was EP processed and RF tested at JLab to evaluate its gradient potential. As shown in Fig. 5, ICHIRO#5 reached a best gradient of 36 MV/m at a  $Q_0$  of  $6 \times 10^9$ . Recently, we have received a new fully featured (with input & HOM couplers) ICHIRO cavity (ICHIRO#7) from KEK.

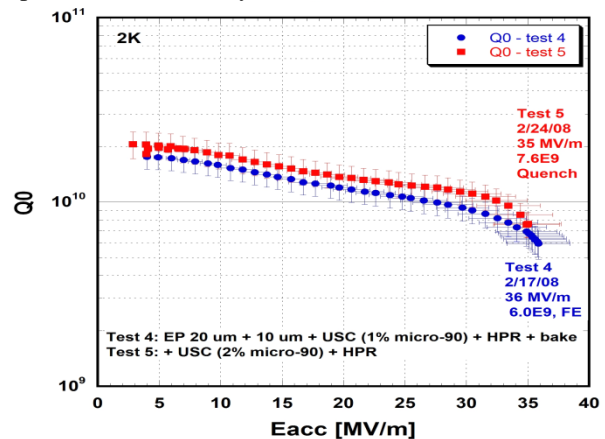


Figure 5: Best performance of ICHIRO#5 during EP processing and RF testing at JLab.

#### Evaluation of JLab In-house Built 9-cell Cavities

Two 9-cell fine-grain cavities (J1 & J2) built by JLab were electro polished and one of them, J2, has been tested. Fig. 6 gives its performance after the 1<sup>st</sup> light EP (less optimal because of unwanted water addition into the acid) and a 2<sup>nd</sup> EP. After a 3<sup>rd</sup> light EP, J2 was found to be limited by mode mixing (the only cavity exhibited mode mixing at JLab and observed in more than one tests).

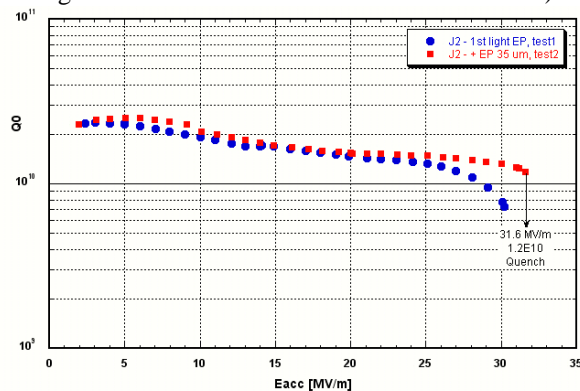


Figure 6: J2 has Q-slope after 1<sup>st</sup> light EP from surface roughening due to unwanted water addition. A 2<sup>nd</sup> and normal light EP improves roughness and RF performance.



## Understanding FE Behaviors and Demonstration of FE Free Performance at $> 35$ MV/m

FE has been reduced in electro polished 9-cell cavities, thanks to the post-EP cleaning procedures. Nevertheless, there are remaining issues needs to be addressed toward the complete FE suppression at very high gradients. For example, we have observed FE turn on caused by low temperature bake out as reported in [9]. Surface studies of niobium samples electro polished together with real cavities reveal niobium oxide granules to be a major source of field emitters (see later section).

Guided by the idea of reducing niobium oxide granules, several techniques have been experimentally found to be useful in reducing FE: (1) re-processing a FE-loaded cavity by additional ultrasonic cleaning and HPR; (2) Light EP processing at lower temperatures; (3) Brushing HOM cans and hooks following the light EP. By applying one or more of these techniques, several examples of FE-free performance at  $> 35$  MV/m have been demonstrated. ICHIRO#5 reached 35 MV/m without detectable X-ray during test 5 shown in Fig. 5; A12 reached 40 MV/m without FE during final test shown in Fig. 3; AES8 reached a FE-free performance during the first power rise up to 36 MV/m (at which point a sudden FE turn on commenced).

### Gradient Limiting Defects in 9-cell Cavities

With the assistance of T-mapping and optical inspection instrumentations, quench limited 9-cell cavities have been studied. A detailed report is contributed to this workshop [10]. An example is given in Fig. 7, showing T-mapping hot spot at the quench location and the long-distance microscope image of the defect observed on the RF surface in the region near the quench location.

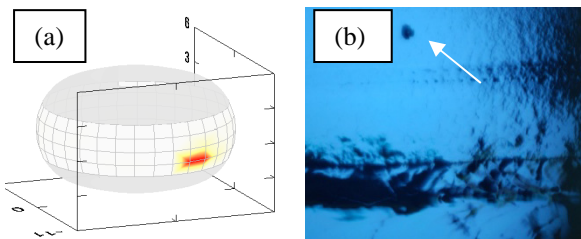


Figure 7: T-mapping and optical inspection of AES5 quench limited at 20 MV/m after the first-pass EP. (a) Quench location determined as a “hot spot” near the equator weld of cell #3. (b) Circular defect (indicated by arrow), 700  $\mu\text{m}$  in diameter, 14 mm away from the weld seam, observed on the RF surface near hot spot location.

Five cavities (AES1, AES3, A15, AES5, AES6) EP processed at JLab are quench-limited below 21 MV/m. The quench locations in these cavities are ultimately all determined by thermometry measurements (AES1 was studied with thermometry at FNAL [11]). Optical inspection of the RF surface at the quench location was ultimately all conducted (AES1 and AES3 inspected at KEK). Here is a summary of facts:

- Outstanding defects are observed within 10 mm distance from the quench location determined by thermometry.
- Defects are of more or less circular shapes with an apparent diameter in the range of 0.3-1mm.
- Defects in AES1 and AES3 are found to be pit or bump, with a depth/height of less than 50  $\mu\text{m}$ . Defect in A15 is a pit with an estimated depth of more than 100  $\mu\text{m}$ . Defects in AES5 and AES6 are not estimated with regard to their profiles.
- Defects are near but outside the complete melted region of the equator EBW. They are not correlated to the overlap of the equator weld. They appear to be observed often in a transition region where apparent grain growth stops.
- Only one defect in one cell limits the entire cavity in A15, AES5 and AES6. Other cells already reached a very high gradient in the range of 28-44 MV/m.

In summary, a consistent pattern seems to be emerging with regard to the size, shape and location of the responsible defects. However, presently it is still premature to draw definitive conclusion. Microscopic and analytical studies of the defect are necessary in the future, even at the cost of sacrificing a 9-cell cavity. The origin of these defects remains unresolved, despite the existence of some models. Nevertheless, it seems that one can argue that a local repair method for defect removal would be useful. In this direction, a local e-beam treatment method is being investigated at JLab [12].

## GRADIENT YIELD CURVE

It is now possible to construct preliminary gradient yield curves. An exemplary yield plot is given in Figure 8 based on actual cavity results obtained at JLab.

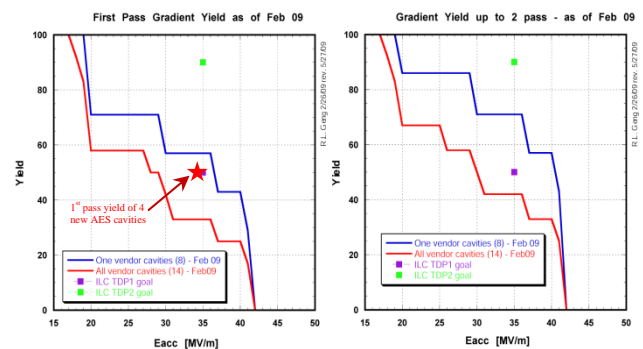


Figure 8: First-pass and second-pass gradient yield based on 14 cavities built by various manufactures processed and tested at JLab as of February 2009. 1<sup>st</sup> pass yield of the 4 new AES cavities (more recent) is shown also.

Despite the relatively small data set, several features of the yield curve are noted: (1) a drop at 20 MV/m (it is understood as described previously that this is caused by sub-mm sized defects near the equator weld); (2) an appreciable increase by re-processing (re-HPR or re-EP) those cavities that fail the first-pass processing.

## FOCUSED R&D WITH 1-CELL CAVITY AND NIOBIUM SAMPLES

### *New Insights into EP Specific Field Emitters*

At JLab, niobium disks (with a typical 25 mm diameter) EP'ed together with 9-cell cavities are subjected to scanning by a high-voltage tip, revealing field emitters. The identified field emitters are further analyzed using SEM/EDX by transporting the sample from the scanning chamber to the integrated SEM chamber. One important finding is the identification (in most cases studied) field emitters to be Nb<sub>x</sub>O<sub>y</sub> granules/clusters (Fig. 9).

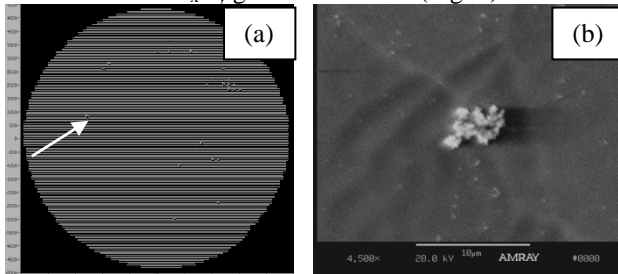


Figure 9: (a) Field emitters revealed by scanning a high-voltage tip over a niobium surface electro polished together with a 9-cell cavity. (b) SEM image of the field emitter (indicated by arrow in Fig. 3a); EDX analysis indicates no foreign elements except niobium and oxide.

A more recent JLab surface study (scanning Auger and SEM/EDX) of niobium samples electro polished at KEK in a cavity-like configuration reveals some interplay between S and Nb<sub>x</sub>O<sub>y</sub> [13]. It is discovered that (1) S distribution is not uniform across the sample surface and in particular some S-enriched regions are centered around Nb<sub>x</sub>O<sub>y</sub> granules; (2) some Nb<sub>x</sub>O<sub>y</sub> granules contain S (again spatially non-uniform). Fig. 10 shows an example of S hiding in Nb<sub>x</sub>O<sub>y</sub> granules.

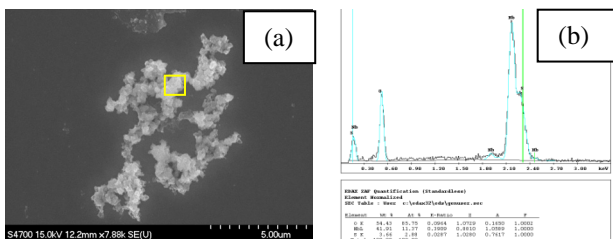


Figure 10: (a) A cluster of Nb<sub>x</sub>O<sub>y</sub> granules with non-uniform S distribution. (b) EDX analysis shows detectable S in the boxed region in Fig. 4a; no detectable S outside the boxed region.

### *Local e-Beam Treatment for Defect Removal*

Guided by the fact that some under-performing 9-cell cavities are limited by only one defect in one cell, we proposed and started to develop a local repair method based on electron beam treatment. Sample studies demonstrated proof of principle and the first 1-cell cavity has been treated recently. RF testing is under way.

### *Integrated Cavity Processing*

We envision an integrated cavity processing concept is the way for future large-scale cavity processing. This necessitates cavity processing in vertical orientation in an integrated fashion. As a first step, vertical EP with acid circulation has been developed. The first 1-cell cavity vertical EP processed at JLab reached a maximum gradient of 44 MV/m limited by quench.

## ACKNOWLEDGEMENTS

Many colleagues at JLab contributed to the work reported here, especially the following people: Gigi Ciovati, Danny Forehand, Byron Golden, Pete Kushnick, Michael Morrone, Roland Overton, Andy Wu and Xin Zhao. We want to give special thanks to our distinguished colleague Curtis Crawford, who is now with FRIB at MSU, for his vital role in enabling major SRF progresses at JLab. Jim Follkie of FNAL worked together with us. We also want to thank Mark Champion of FNAL and Hitoshi Hayano, Takayuki Saeki, Fumio Furuta and Kenji Saito of KEK for fruitful collaborations.

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