PROGRESS ON IMPROVING SC CAVITY PERFORMANCE FOR ILC*

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Abstract

A major portion of the ILC R&D effort is focused on increasing the sustainable gradients in the baseline TESLA-shape SC cavities. This is a world-wide effort with major contributions from DESY (in parallel with their XFEL program), JLAB, FNAL, KEK and Cornell University. During the past year, the work in the US and Japan has ramped up considerably, and PAC09 is an opportune time to review the contributions from the groups in these regions, as well as at DESY.

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 [1]. Successful 9-cell cavity results of a DESY/KEK led collaboration provided the proof-of-existence of 35 MV/m by using electropolishing (EP) surface processing and low temperature bake treatment [2]. 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. A major focus is to improve the gradient yield. In the mean time, one should be reminded that a broader range of SRF cavity R&D topics are being addressed in support of ILC, such as alternative cavity shapes (Low-Loss/ICHIRO and Re-entrant) and large-grain niobium material [3]. The alternatives are relevant to the ILC gradient goal in terms of reaching higher gradient (new shape cavities) or reaching the same gradient at potentially lower cost (large-grain material). In this paper, we will review the gradient progress with a focus on the base line shape (TESLA), material (fine-grain niobium) and processing (EP).

The past 2-3 years saw a considerable growth in the ILC cavity effort in the Americas and Asia region. Together with the strong Europe effort (in parallel with XFEL), a fairly large number of 9-cell cavities were fabricated, processed and tested. DESY received 30 cavities manufactured by two European cavity vendors for the 6th production. FNAL received 24 cavities produced by various sources including the first batch from a cavity vendor in the US industry. KEK received 14 (among which 6 are TESLA-like shape and 8 are ICHIRO shape) cavities manufactured by Japanese cavity vendors. It is worth mentioning that additional new cavities are emerging in other Asian labs. For example the first 9-cell TESLA-shape cavity was successfully built in China by Peking University [4]. The first 9-cell ICHIRO-shape cavity was built in Korea by PAL in collaboration with KEK [5].

SITE INDEPENDENT DEMONSTRATION OF 35 MV/M IN 9-CELL CAVITIES

A major recent progress in ILC cavity gradient R&D is the successful realization of 35 MV/m in multiple 9-cell cavities in the America region under the collaboration between JLab and FNAL. This site-independent demonstration (besides DESY/KEK) of 35 MV/m increases our confidence in the ILC goal gradient choice.

Six 9-cell TESLA-shape fine-grain cavities purchased by FNAL from a European cavity vendor (A6, A7, A11, A12, A13, A14) reached a best gradient of more than 35 MV/m at JLab. 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 (typical 2% by volume) [6]. The JLab cleaning and assembly procedure, along with the advanced EP procedure, ensured a significant reduction in field emission (more in later section) and enabled the realization of > 35 MV/m in four 9-cell cavities (out of 5 manufactured by one vendor) following the first light EP. Fig. 1 shows the Q(Eacc) curves of these cavities. Note that the final performance of A12 is shown, which is obtained after a second light EP. A15 is quench-limited by a defect in cell #3 (see later section).

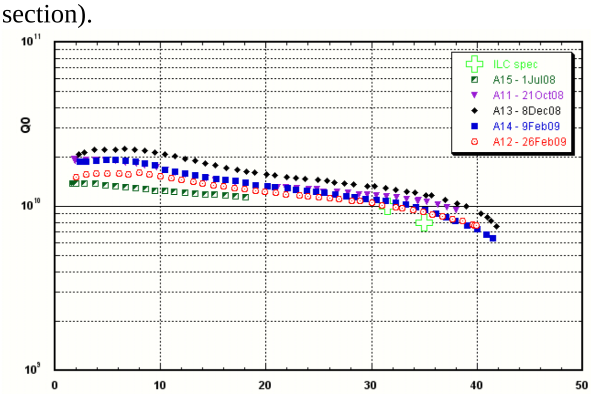

Figure 1: Performance of 5 cavities manufactured by one vendor and EP processed and tested recently at JLab. Error bars are not shown for clarity.

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FIELD EMISSION

The necessity for reducing field emission (FE) in electropolished 9-cell cavities was already well known from early experiences [7].

Two post-EP cleaning methods have been applied successfully for routine 9-cell processing: alcohol rinsing at DESY and ultrasonic cleaning in detergent solution at JLab [8].

These two methods reduce FE in electropolished 9-cell cavities. For example, less than 15% of 9-cell cavity tests at JLab are limited by FE. More recently, JLab demonstrated a successful 9-cell test with *no detectable Bremsstrahlung X-ray* up to 40 MV/m (A12 as shown in Fig. 1).

The effectiveness of alcohol rinsing at DESY can be seen in Fig. 2 [9], in which FE onset and maximum gradient of some recent 9-cell cavities are shown. It is noticed that 11 out of 15 electropolished cavities have no FE (see Ref. [10] for definition of FE onset).

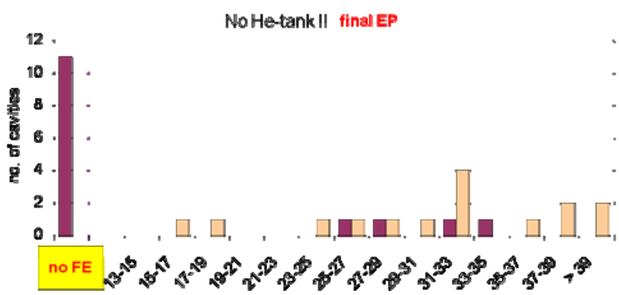

Figure 2: FE onset and maximum gradient of some recent 9-cell results at DESY.

It should be also mentioned that some single-cell cavity experiments at KEK have shown clearly that FE can be reduced by performing the final EP very briefly with freshly mixed electrolyte [11]. However, this “fresh EP” method has not yet been successfully demonstrated for 9-cell cavity processing.

In parallel to the successful experiments with a large number of real 9-cell cavities for the post-EP cleaning procedures as described above, some R&D effort has been focused on understanding the source of FE.

Sulfur (S) has been identified for a long time as a contaminant on electropolished surfaces [12][13][14]. In fact, S is generated at such a high rate that, after a typical heavy EP of a 9-cell cavity, yellow deposit (elemental S) can be readily observed with naked eyes on various surfaces such as the cathode-shielding Teflon mesh and cavity-supporting end groups. The effectiveness of alcohol rinsing is explained by the fact that elemental S is soluble in alcohol. A recent study at KEK suggested that S removal by alcohol rinsing can be further enhanced when assisted by ultrasonic vibration [15].

At JLab, niobium disks (with a typical 25 mm diameter) electropolished together with real 9-cell cavities are subjected to scanning by a high-voltage tip (for a DC field up to 140 MV/m across the tip and niobium surface). This reveals 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 without breaking the vacuum. One important finding is the identification (in most cases studied) field emitters to be Nb_xO_y granules/clusters. One example is given in Fig. 3.

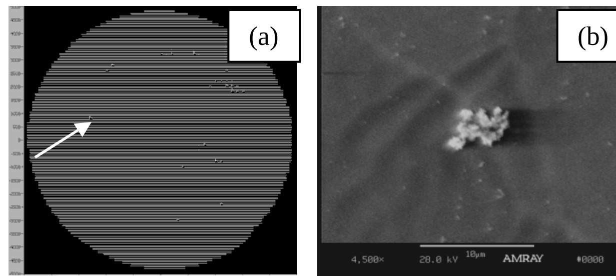

Figure 3: (a) Field emitters revealed by scanning a high-voltage tip over a niobium surface electropolished together with a 9-cell cavity. (b) SEM image of the field emitter (indicated by arrow in Fig. 3a); EDX analysis indicates no foreign elements except niobium and oxide.

Since Nb_xO_y is an intrinsic intermediate product in the EP process, experiments were carried out at JLab to explore improved EP processing parameters for reduced Nb_xO_y. This resulted in an advanced procedure of EP at lower temperatures in conjunction with extended period of acid circulation after the voltage is turned off during the EP process. The significant FE reduction in recent 9-cell cavities at JLab is attributable to the advanced EP procedure.

A more recent JLab surface study (scanning Auger and SEM/EDX) of niobium samples electropolished at KEK in a cavity-like configuration reveals some interplay between S and Nb_xO_y [16]. 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_xO_y granules; (2) some Nb_xO_y granules contain S (again spatially non-uniform). Fig. 4 shows an example of S hiding in NbxOy granules.

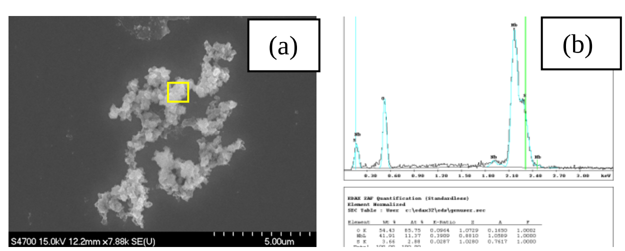

Figure 4: (a) A cluster of Nb_xO_y granules with non-uniform S distribution. (b) EDX analysis shows detectable S in the boxed region in Fig. 4a; no detectable S outside the boxed region.

These new surface study results suggest that a thorough removal of both S and Nb_xO_y is likely an efficient path for further FE reduction. It is advisable to accomplish this by applying the existing post-EP rinsing procedures in conjunction with advanced EP processing demonstrated at JLab as described above. One can also expect improvement by alternative cleaning techniques such as the sponge cleaning method currently being explored at KEK [17].

QUENCH

The gradient of some 9-cell cavities processed and tested in the past years is limited by quench (often times without field emission).

For example, two early 9-cell cavities (AES1 & AES3) EP processed at JLab were quench limited at <20 MV/m. Through pass-band measurements, the π-mode gradient limitation was found to be caused by specific cell pairs and was insensitive to repeated EP processing. By further RF testing at FNAL & JLab with thermometers attached to the suspected cells, the quench location in these two cavities was identified to be near (but outside) the equator weld of cell #3 and #4 (counted from the RF input coupler port side), respectively [18][19]. The RF surface of AES1 was ultimately inspected by using a new optical inspection tool developed by KEK and Kyoto University [20]. The responsible defects turned out to be circular spots 400-600 μm in diameter. These defects also have structure in the normal direction with characteristic dimension of about 40 μm.

These early encouraging results demonstrated the effectiveness of thermometry and optical inspection for improved understanding of the quench limit in 9-cell cavities. Later world-wide gradient R&D was quickly enhanced with various temperature measurement instrumentation, "T-mapping", for locating defects and optical inspection tools for the purpose of identification and documentation of responsible defects (see Fig. 5).

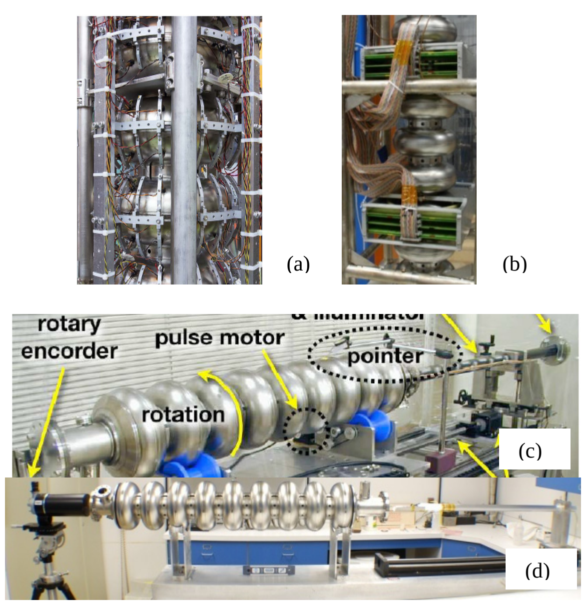

Figure 5: T-mapping systems at KEK (a) and JLab (b) and optical inspection tools at KEK (c) and JLab (d).

JLab developed a T-mapping system, consisting of two sets of fixed thermometry boards that can be attached to any two cells. Each board hosts 160 carbon resistors, fully covering the equator and the neighborhood area [21]. This system not only captures quench events but also provides pre-cursor heating at quench locations. JLab also developed a long-distance-microscope-based optical inspection system with a resolution up to 3μm [22]. These systems are routinely used for 9-cell cavity program at JLab to study 9-cell cavities not meeting the ILC gradient specification after the first-pass EP processing. Three cavities (A15, AES5, AES6) that are quench limited below 20 MV/m have been successfully studied. In all cases, the quench is caused by *a single defect in only one cell*. The other 8 cells typically reach a high gradient of 28-34, 31-44 and 32-44 MV/m respectively after the first-pass EP processing. These circular defects (typically 400 μm – 1mm in diameter) are near but outside the fully melted region (typically 4mm in width) of the equator electron beam weld (EBW). The result of A9 was already published and can be found in Ref. [22]. Here we show a new T-mapping and optical inspection result of AES5 in Figure 6. The result of AES6 is similar to that of AES5.

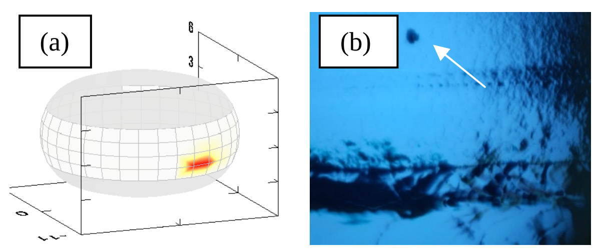

Figure 6: T-mapping and optical inspection of AES5 quench limited at 20 MV/m after the first-pass EP processing. (a) Quench location determined as a "hot spot" near the equator weld of cell #3. (b) The circular defect (indicated by arrow), 700 μm in diameter, 14 mm away from the weld seam, observed on the RF surface at hot spot location.

The Cornell SRF group developed a system for quench location detection using the second sound [23]. 8 oscillating superleak transducers are used to capture quench events at any cell of a 9-cell cavity. This system has been used for several cavity tests. One example is the successful quench location determination in the end cell of a 9-cell re-entrant shape cavity. Through optical inspection (long-distance-microscope based system), an elliptical defect (120μm×60μm) is observed near (but outside) the equator weld.

KEK developed a T-mapping system based on 300 carbon resistors covering the entire 9-cells [24]. An optical inspection tool has been developed [20] and is routinely used at KEK as well as at DESY and FNAL. New cavities fabricated at MHI are successfully studied. For example, MHI5 is found to be quench limited at 20-27 MV/m and the quench location was detected near the equator EBW. Through optical inspection, variable width of EBW is observed at the quench location.

DESY has been using a T-mapping system for a long time. It is based on rotating sensors covering the entire 9-cells. Numerous 9-cell cavities have been studied. Some of them were inspected after the DESY test at KEK using the optical inspection system described previously. The quench limited cell of a 9-cell cavity was cut off and a surface analysis was performed showing detailed geometrical structure and chemical composition of the defect. A new cavity study (Z137) at DESY reveals the quench (25 MV/m) location has significantly roughened grains following the heavy EP [25].

FNAL is developing a T-mapping system based on 8640 fixed diode sensors covering the entire cells. Initial test with 1-cell cavities has been conducted. LANL is also developing a 9-cell T-mapping system [26].

In summary, an improved understanding of the quench limit is emerging as a result of the global R&D effort for ILC. In several cases, the source of the quench limit at ~ 20 MV/m resides in only one cell with the remaining 8 cell reaching already gradients exceeding 30 MV/m. The responsible defects are near the equator EBW. The location is outside of the completely melted region and coincides with the transition region where the grain growth stops in the heat affected zone. Most observed defects are circular in shape with a diameter of less than 1mm. Although many cases studied so far are cavities fabricated by new vendors, this kind of defect is also observed in cavities built by "qualified" vendors. It is conjectured that these observed defects are originated from the EBW process during the cavity manufacture. Further studies are under way in verifying this theory by systematic optical inspection of cavities and tracking and correlating the observed features with the quench limit.

The discovery of single point defect in only one cell causing the quench limit has important application in future effort for further improving the gradient performance. A "local repair" seems to be an efficient path. By removing the responsible defect in cavities failing to meet the ILC specification after the first-pass processing, one may expect to raise the gradient performance with a second-pass processing.

GRADIENT YIELD

The ultimate goal for the ILC cavity gradient R&D as stated in the ILC research and development plan for the technical design phase is to reach a production yield of 90% at 35 MV/m at a Q_0 of 8×10^9 (31.5 MV/m at 1×10^{10}) during the vertical acceptance test [27]. The cavity manufacture and processing are both important in realization of this ambitious goal. A uniform specification for cavity manufacture and processing is necessary for a consistent gradient yield evaluation. However, it is now possible to construct preliminary gradient yield curves based on the actual gradient results in the past several years for the purpose of understanding the status of the gradient R&D. An exemplary yield plot is given in Figure 7 based on the cavity results obtained at JLab.

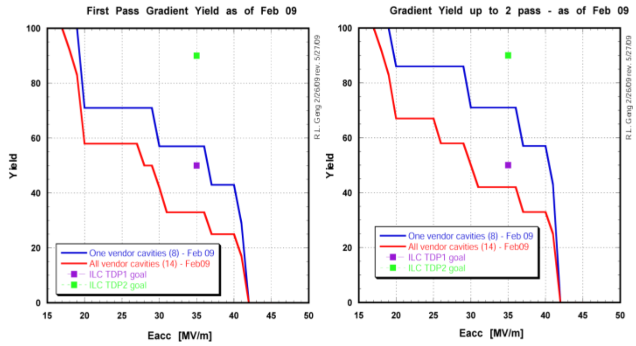

Figure 7: First-pass and second-pass gradient yield based on 14 cavities built by various manufactures (8 from a European vendor, 4 from a US vendor, 1 from a Japan company and 1 from Jefferson Lab) processed and tested at JLab as of February 2009.

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; (3) a clear gap between cavities manufactured by the experienced one vendor and the "new" vendors.

OUTLOOK

In the coming years, one expects a rising gradient R&D effort toward the realization of the ILC cavity gradient goal.

Some 60 9-cell cavities are to be manufactured by vendors in three regions. In addition, 800 cavities are to be built for the European XFEL project. These new cavities will increase the global data set for credible gradient yield evaluation. They will also provide opportunities for new vendors to improve and master the manufacture practice. It is expected that the knowledge obtained by laboratories in the past and coming years in the nature of gradient limiting defects will be fed back to the industry. A close collaboration between laboratories and the industry would be a necessary step for moving forward.

Significant SRF infrastructure is ramping up in the Americas and Asia regions. FNAL has successfully commissioned the cavity processing and testing facilities, including the FNAL/ANL EP machine, HPR machines, and vertical cavity test area [28]. Excellent single-cell cavity results have been reported. Routine 9-cell EP processing and testing are expected to be happening in the near future. KEK has successfully commissioned the STF facility, including the in-house EP machine, HPR machine and vertical cavity test facility [29].

SUMMARY

35 MV/m in 9-cell cavities has been demonstrated site-independently. In total, more than 24 cavities have achieved the ILC gradient specification.

Progress has been made in understanding quench and FE behaviors in 9-cell cavities. Significant reduction in FE in 9-cell cavities has been observed thanks to the post-EP cleaning procedures. Further improvement is expected by advanced EP procedures as well as alternative cleaning procedures. T-mapping and optical inspection are now routinely used for under-performing cavities. The source of quench in several cavities is identified to be sub-mm sized defects near but outside the equator EBW. A single point defect in one cell often is responsible for the quench limit with the remaining eight cells already reaching a gradient higher than 30 MV/m after the first-pass processing. Local repair methods such as local grinding and local E-beam re-melting are being explored for removal of these defects. Global repair method such as tumbling is also being explored with the successful first demonstration at Cornell University [30].

Significant SRF infrastructures are ramping up in the Asia and Americas regions. Some 60 9-cell cavities are expected to be manufactured by industry in three regions in the coming years. Preliminary gradient yield analysis at DESY and JLab shows that the ILC gradient yield seems to be within reach.

Lastly, we want to mention that progress has been also made in alternative technologies such as large-grain material and low-loss shape cavities.

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