ROOT CAUSES OF FIELD EMITTERS IN SRF CAVITIES PLACED IN CEBAF TUNNEL*

R.L. Geng#, JLAB, Newport News, VA 23606, U.S.A.

Abstract

It has been suspected that appearance of new field emitters can occur in SRF cavities after their placement in accelerator tunnel for long term beam operation. This apparently has been the case for CEBAF. However, no physical evidence has been shown in the past. In this contribution, we will report on the recent results concerning the root cause of field emitters in SRF cavities placed in CEBAF tunnel. We will discuss these results in the context of high-reliability and low-cryogenic-loss operation of CEBAF.

INTRODUCTION

Field emission (FE) in an SRF cavity often has its root in small foreign particulate. To avoid particulate contamination, present day SRF cavities are cleaned and handled using strict procedures. Nevertheless, optimally clean cavity surface is still difficult to obtain at the point of a cavity being ready for beam in the accelerator tunnel. Moreover, a number of beamline components may generate particulates, some of which may be transported to sensitive cavity surface areas, becoming new field emitters. Not all the particulates on the sensitive cavity surface are readily field emitters. Some non-field-emitting particulates can be *activated* by frozen gases [1].

From the decades-long history of running the large-scale SRF machine CEBAF, it has been known that, on average, FE onset gradient in cavities indeed deteriorated between cavity qualification test to their placement in the accelerator tunnel and henceforward. This deterioration caused a rapid increase in the FE current, resulting in increased machine interlock trips via its charging effect on cryogenic ceramic RF windows in the original 5-cell cavities [2]. To reduce the machine trip rate, the gradient of some cavities is administratively lowered, resulting loss in the linac voltage. CEBAF is predicted to lose an acceleration voltage of 34 MV/pass-year from the total of 320 original 5-cell cavities [3]. In the past, the “lost” voltage was recovered by cavity in-situ helium processing [4] or cryomodule refurbishment [5].

The root causes of FE onset deterioration in the original CEBAF cavities have been unknown. In the past few years, 88 cutting-edge 7-cell niobium cavities have been added to CEBAF for its 12 GeV energy upgrade [7]. These cavities are specified to operate in the CW mode at a gradient of 19.2 MV/m. This is a dramatic leap-forward in gradient performance for CW SRF application. The corresponding peak surface electric field of ~ 40 MV/m is significantly higher than the typical values of 25-30 MV/m in the original 5-cell cavities. Due to the exponential nature of FE, the new 7-cell cavities are therefore at a higher risk of FE onset degradation as compared to the original 5-cell cavities, if the root cause is the same. Presently, there are 418 SRF cavities in total placed in the CEBAF tunnel. To meet the challenge of operating these cavities reliably for 12 GeV physics, it is necessary to understand the root causes of field emitters in SRF cavities placed in CEBAF tunnel, which is the subject of this contribution.

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#geng@jlab.org

PHENOMENA LINKED TO FE PRODUCED BY NEW 7-CELL CAVITIES

Beamline Vacuum Pressure Rise

A correlation between the beamline vacuum and the 7-cell cavity gradient was observed during commissioning of the upgrade module C100-10 placed in the zone 1L26 in the north linac [8]. A sharp rise in the beamline vacuum pressure above the background level occurred when the cavity gradient was raised by a small (1-2 MV/m) amount beyond a threshold. As the CEBAF interlock system would shut off the RF power when the beamline vacuum pressure reached the nominal set threshold of 1×10^{-7} Torr, the pressure then recovered quickly after the cavity field was emptied. This process is illustrated in Fig. 1. The observed beamline vacuum pressure rise is consistent with gas desorption from the beamline inner surfaces stimulated by FE electrons. Simulation studies have shown that some electrons emitted from the iris region of a 7-cell cavity escape the cavity, reaching the beamline components outside the cavity string [9][10].

As the CEBAF interlock is presently configured in such a way that a beamline vacuum pressure exceeding 1×10^{-7} Torr will also trigger closure of beamline gate valves, trip events shown in Fig. 1 would cause a secondary effect of particulate generation. We will return to this point later.

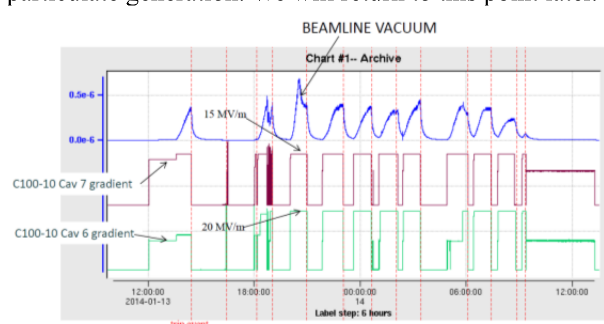

Figure 1: Beamline vacuum pressure rise in Zone 1L26 correlated with cavity gradients.

Vapor Formation in Helium-II

It has been known in the community that, a cavity placed in a cryomodule can be constrained by a limit related to vapor formation in He-II. This phenomenon seems to have been observed in horizontal cryomodule testing of 7-cell cavities at JLab [11]. In such a configuration, vapor formation is induced when heat enclosed within the cavity helium vessel exceeds a threshold, determined by the diameter of the riser pipe which connects the cavity liquid helium vessel and the two-phase-helium pipe (see Fig. 2).

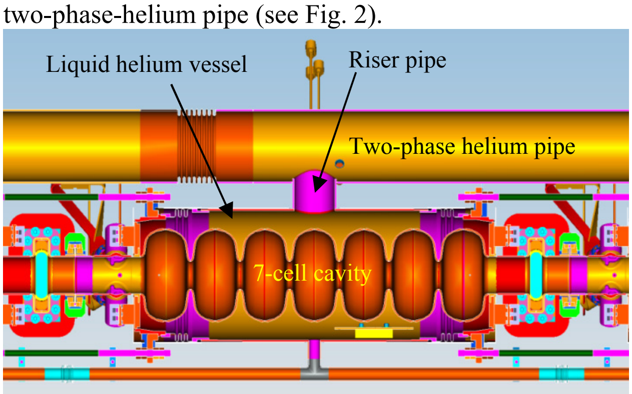

Figure 2: Configuration of liquid helium vessel and two-phase helium pipe around a CEBAF upgrade 7-cell cavity.

The critical heat flux for vapor formation is ~1 W/cm^2 at CEBAF operation temperature 2.07K [12][13]. The design riser size provides sufficient coverage for dynamic heat load (cavity and coupler) corresponding to the design Q_0 of 7×10^9 at the design gradient as well as static heat load, with ~20 W margin permitted to accommodate other heat load such as the applied resistive heat required by cryo-plant control. However, FE arisen from field emitters introduced after cavity vertical test may produce unplanned heat possibly well beyond the 20 W margin. A numerical computation predicts 20-100 W heat load due to FE dissipation at a gradient of 15 MV/m [9].

TRACKING FE ONSET DEGRADATION

By now, the 88 new 7-cell cavities have accumulated some beam operation experience in CEBAF tunnel since their placement in period of 2011-2012. Although some cavities exhibited marginal improvement in FE onset, on average, degradation is observed. Fig. 3 shows the average FE onset degradation between four measurement points: (1) individual cavity qualification in VTA facility [14]; (2) cryomodule acceptance in CMTF facility; (3) commissioning of cryomodule as-placed in tunnel; (4) re-verification in tunnel after 3-4 years of operation.

As one can see from Fig. 3, large degradation (6 MV/m) is observed from VTA to CMTF test. Additional degradation of ~ 2 MV/m is observed between CMTF test and commissioning in CEBAF tunnel. 3-4 years after cavities placement in the tunnel, yet another average degradation of ~ 1 MV/m was observed from, based on data from six modules.

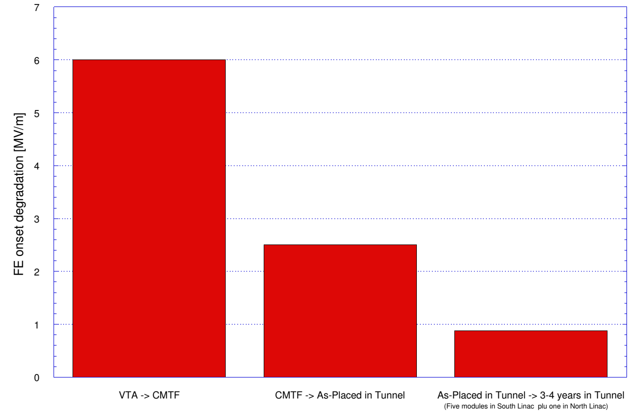

Figure 3: Observed average FE onset degradation between four checking points for the eighty new 7-cell cavities.

ROOT CAUSES OF FIELD EMITTERS

Field Emitters Introduced Prior to Module Placement in CEBAF Tunnel

It is clear that introduction of field was dominated by processes before a module was readied for beam. This is consistent with the picture that: (1) introduction of field emitters was dominated by the process of cavity string and beamline UHV related cryomodule assembly; (2) additional field emitters were introduced during the process of cryomodule transportation and installation in the tunnel as well as the warm girder beamline UHV component installation.

Field Emitters Introduced After Module Placement in CEBAF Tunnel

The observed ~1 MV/m degradation in FE onset after the modules were placed in CEBAF tunnel, over a period of 3-4 years of initial operation, is not a surprise, given the observed FE onset degradation in original CEBAF cavities [3]. This is consistent with a picture that one or more of the following mechanisms were at work: (1) new field emitters were *added* to sensitive cavity surfaces; (2) particulates pre-existing outside of cavities were *transported* to sensitive cavity surfaces; (3) Dormant field emitters pre-existed on cavity surfaces and were *activated* by change in conditions such as frozen gas accumulation.

Sources of Particulate Field Emitters

Figure 4 shows the correlation between the FE onset degradation and the cavity location. It seems particulates might be added more preferentially in cavity at location #8 due to cavity-string evacuation. The upgrade cavity strings were assembled in the old clean room, which was later on replaced by a new one due to the TDEF project. Whether this has any effect will be answer by test results of the on-going LCLS-II cryomodules.

Figure 5 shows the change in FE onset over the first 3-4 years of operation for 48 7-cell cavities contained in six new modules. It seems that field emitters introduced after module placement in tunnel are not limited to cavities at the ends of the module.

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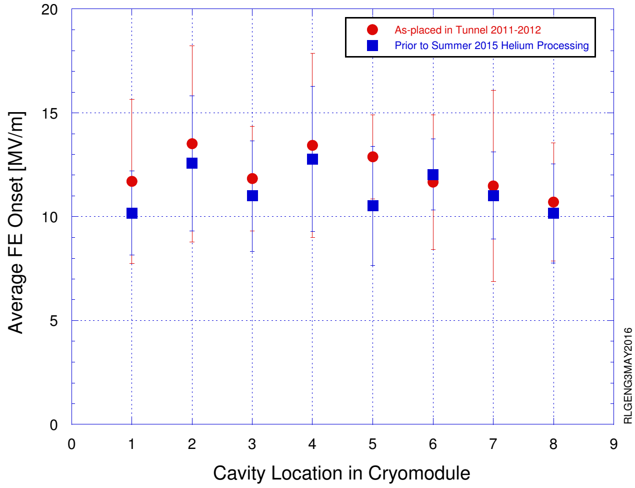

Figure 4: Correlation between FE onset degradation and cavity location in cryomodule.

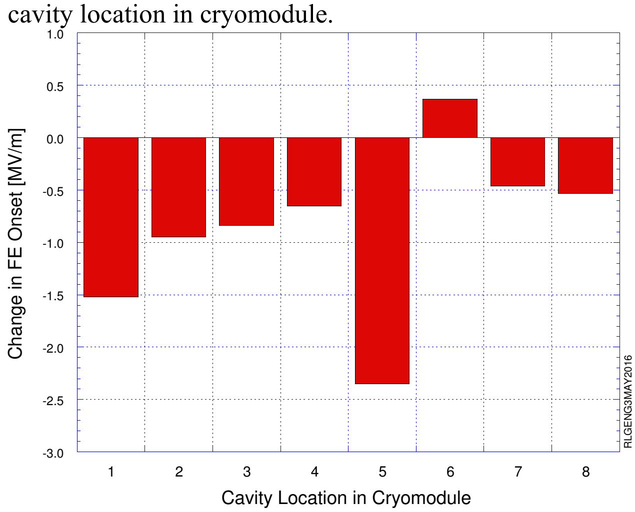

Figure 5: Change in FE onset of 48 7-cell cavities from 3-4 years of operation in tunnel.

Transportation of Particulate Field Emitters in Cavities Placed in CEBAF Tunnel

Recently, a CEBAF-style module FEL02 was studied by collecting particulates [6]. Particulates bearing Ti/Ta (see Fig. 6) of a few micron in size were found from all studied cavities at location #1, #2, #7, and #8.

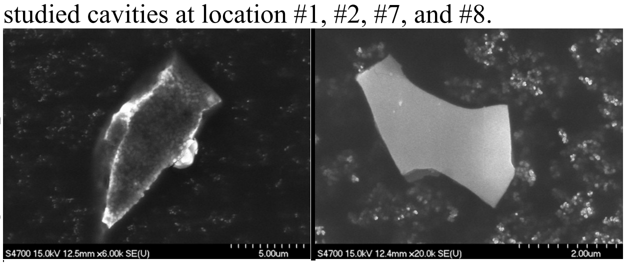

Fig. 6 Microscopic particulates bearing Ti/Ta collected from cavity at location #7 (L) and #1 (R).

The only possible source of Ti/Ta particulates is the differential (DI) ion pump (IP) attached to the beamline pump-out manifold at the helium supply-end-can side and is next to the cavity at location #8. The fact that Ti/Ta particulates were found in the cavity at location #1, being more than 7 meter away from the source IP, suggests that these particulates were *transported* from their source location to destination. The transportation mechanism is unknown. Particulate generation from ion pumps is well known and documented [17][18].

Field Emitter Activation by Frozen Gases

The role of frozen gases in FE onset degradation in CEBAF cavities is presently unknown. SRF cavities installed in storage rings are reported to benefit from partial warmup or full room temperature warmup [19][20]. This procedure is known to remove frozen gases (H_2, CO, CO_2, H_2O) from the cavity surface as well as the RF input coupler surface [21].

MITIGATION AGAINST FE ONSET DEGRADTION IN CEBAF SRF CAVITIES

Increasingly it has been realized that field emission is a central issue faced by CEBAF. Its resolution is valuable in order to achieve high-reliability and low-cryogenic-loss operation of CEBAF at required 12 GeV beam energy. To that end, some near term changes are needed. Over the longer term, it is necessary and possible to reverse the degradation by developing new techniques of in-situ particulate removal from cryomodules effectively.

The Following changes should be made immediately:: (1) Stop the practice of "Hi-potting" ion pumps. Particulate generation from this practice is not proven but it is highly likely; (2) Stop the frequent cycling of beamline gate valves. Closing these valves (VAT mini UHV with Viton gasket seal) is known to generate stainless-steel and Viton particulates [22]; (3) Develop a new apparatus and a new procedure to be implemented for all future beamline UHV components maintenance.

The following studies should be launched as soon as possible: (1) Examine the effect of controlled cryomodule warm-up to a temperature up to 300K; (2) Determine the source of field emission degradation during the string assembly and tunnel installation; (3) Develop the next generation beamline UHV system; (4) Develop a model of particulate transportation; (5) Develop novel techniques for particulate removal from a cryomodule in-situ without full module disassembly.

CONCLUSION

In conclusion, it was found out that, till now 90% and 10% FE onset degradation in the newly installed 7-cell cavities occurred before and after, respectively, the cryomodule placement in the CEBAF tunnel. This implies that field emitters were predominantly introduced before these modules were settled in the tunnel. Field emitters introduced thereafter are not insignificant and their possible sources are identified. Our current understanding of root causes of field emitters in cavities placed in CEABF tunnel is not yet complete and further studies are needed. Such studies are valuable to guide development of mitigations so as to end adding new field emitters as well as to remove inherited emitters in future cryomodule operation and maintenance.

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