ROOT CAUSES OF FIELD EMITTERS
IN SRF CAVITIES PLACED IN CEBAF TUNNEL*
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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, lodging on the cavity inner surface. To avoid particulate contamination, present day SRF cavities are cleaned and handled using strict procedures. Nevertheless, owing to the complex nature of post-individual-cavity-qualification string assembly and system integration, 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. But some non-field-emitting particulates can be activated by frozen gases [1]. This effect makes the control of FE in operating SRF cavities very dynamic and more challenging, as there maybe a variety of intrinsic sources for residual gases in an operational SRF system.

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, due to the exponential nature of the FE process, resulting in increased machine interlock trips via its charging effect on cryogenic ceramic RF windows in the original 5-cell cavities [2]. To support desired productive physics runs, the machine trip rate needed to be constrained. This was achieved by administratively lowering the operation gradient of some heavily field emitting cavities, therefore at the cost of losing the linac voltage. Based on the past cavity performance data, CEBAF is predicted to lose an acceleration voltage of 34 MV/pass-year from the total of 320 original 5-cell cavities installed in the north and south linacs [3]. To preserve the machine energy reach, the “lost voltage” must be restored. In the past 4-6 GeV CEBAF era, this had been successfully achieved by FE mitigation via cavity in-situ helium processing [4] or cryomodule refurbishment [5].

The root causes of FE onset deterioration in the original CEBAF cavities have been known. 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.

PHENOMENA LINKED TO FE PRODUCED BY NEW 7-CELL CAVITIES
The operation experience of the new CEBAF upgrade high-gradient 7-cell cavities is still in its early stage [8]. Nevertheless, some new phenomena linked to FE produced by these cavities have been observed.

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. The pressure rise would continue even when the gradient was later held at a constant level. 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. From the initial commissioning test of the cryomodule C100-10, the FE onset of cavities C100-10-6 and C100-10-7 was measured to be 20 and 12 MV/m, respectively. The observed beamline vacuum pressure rise is consistent with gas

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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 $1 \times 10^{-7}$ 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.

**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, therefore its intrinsic high gradient capability found during its initial vertical qualification testing, becomes no longer accessible for exploitation. 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).

The critical heat flux for vapor formation is ~1 W/cm² at CEBAF operation temperature 2.07K [12][13]. The riser pipe diameter for the CEBAF upgrade cavity is 82 mm. This design provides sufficient coverage for dynamic heat load (cavity and coupler) corresponding to the design $Q_{0}$ of $7 \times 10^9$ at the design gradient as well as static heat load. A ~ 20 W margin is permitted to accommodate other heat load such as the applied resistive heat required by cryo-plant control. As is well known, the heat load by FE dissipation rises rapidly with gradient due to the exponential nature of the FE process, FE arisen from field emitters introduced after cavity vertical test may produce unplanned heat possibly well beyond the 20 W margin, setting off vapor formation. For example, a numerical computation of a typical field emitter located in the iris region of the CEBAF 7-cell cavity predicts 20-100 W heat load due to FE dissipation at a gradient of 15 MV/m [9].

The gradient limit caused by FE-induced heating vapor formation can be mitigated by lowering the cavity bath temperature as the critical heat flux peaks at 1.5 W/cm² at 1.9K. But the gain is expected to be less effective when FE loading dominates.

**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. This allows an opportunity to assess the FE evolution over the time span from the individual cavity acceptance to the point of years of operation. 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 vertical qualification test in VTA facility [14]; (2) cryomodule acceptance test in CMTF facility; (3) commissioning test of cryomodule as-placed in tunnel; (4) re-verification test in tunnel after 3-4 years of operation.

![Figure 3: Observed average FE onset degradation between four checking points for the eighty new 7-cell cavities.](image-url)

As one can see from Fig. 3, large degradation (6 MV/m) is observed from VTA test to CMTF test. This is not a surprise, and it is a known challenge in the community to preserve cleanliness initially achieved in individual cavities. There are many assembly steps required between individual cavity qualification testing in VTA and cryomodule acceptance testing in CMTF. Additional degradation of ~ 2 MV/m is observed between CMTF test and commissioning test in CEBAF tunnel.
Prior to summer 2015, six modules, including all five modules in the South Linac and one in the North Linac were re-checked in preparation for helium processing, yet another average degradation of ~ 1 MV/m was observed. With the FE onset degradation before and after cavity placement in tunnel separated, we now switch to examination of the possible root causes of field emitters.

ROOT CAUSES OF FIELD EMITTERS

Field Emitters Introduced Prior to Module Placement in CEBAF Tunnel

Out of the observed ~10 MV/m total average degradation in FE onset, ~8 MV/m results from activities prior to the module commissioning test in the tunnel. Therefore it is clear that introduction of field emitters in the upgrade 7-cell cavities was dominated by processes before a module was readied for beam.

Out of this pre-operation 8 MV/m degradation, 6 MV/m is observed prior to CMTF testing. 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

We have indirect and direct evidence with regard to the sources of particulate field emitters.

Fig. 4 shows the correlation between the FE onset degradation and the cavity location in 12 GeV upgrade cryomodules. There seems to be a tendency (red series) that the initially placed cavity at location #8 has the lowest FE onset. This is consistent with the picture that particulates might be added more preferentially by: (1) the process of cavity-string evacuation, which was done by pumping from the end of cavity #8; (2) the process of re-starting the ion pump when the cryomodule was settled in the tunnel. As part of the pump-out manifold, this ion pump serves the purpose of maintaining cavity string vacuum. The current design configuration is such that there is no isolation between this ion pump and cavities.

It might be worth mentioning that 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 4: Correlation between FE onset degradation and cavity location in cryomodule.](image)

From Fig. 4, one can also see (blue series), after 3-4 years of cryomodule operation in the tunnel, the FE onset becomes more or less evened out across the entire module. This is consistent with the picture that field emitters introduced after module placement in tunnel are not limited to cavities near the ends of the module. This can be seen more clearly in Fig. 5 (red series) which shows the change in FE onset of the 48 7-cell cavities contained in the five modules in South Linac and one module in North Linac.

![Figure 5: Change in FE onset of 48 7-cell cavities from 3-4 years of operation in tunnel.](image)

Transportation of Particulate Field Emitters in Cavities Placed in CEBAF Tunnel

Before the discussion of particulate transportation in cavities placed in CEBAF tunnel, let’s first recall a recent
result on particulates collected from the inner surface of cavities in a module previously operated with beam [6]. This module dubbed as FEL02 is currently being refurbished as the next replacement module for CEBAF (so called C50-12). Its design is identical to the standard original CEBAF cryomodule except some deviation in higher-order-mode dampers etc. In order to gain an understanding of the root cause of particulate field emitters in a CEBAF-style cryomodule, a study was launched to collect particulates from cavity surfaces for analyzing. The detailed results are reported in Ref. [6]. Here we show an outstanding one which proves the transportation of particulates generated by the beamline ion pump. Four cavities at location #1, #2, #7, #8 were studied. Particulates bearing titanium/tantalum of a few micron in size were found from all of these cavities. Shown in Fig. 6 are two example particulates, one from cavity IA355 (location #7); the other from cavity IA351 (location #1).

As the DI IP was located further upstream beyond cavity at location #1, those titanium/tantalum particulates collected from cavities at location #7 and #8 most likely have nothing to do with the shockwave event. An unknown mechanism must have been in effect to transport these microscopic particulates from the source IP to the cavities 7 meters away! We speculate this mechanism is related to particulate charging by ionization radiation and particulate levitation because of attraction between the charged particulates and the main accelerated electron beam. We believe the same particulate transportation mechanism is at work in CEBAF and FEL02 modules owing to design similarity. Particulate generation from ion pumps is well known and documented [18][19].

Field Emitter Activation by Frozen Gases

It is known that a dormant particulate can be turned into an active field emitter by activation due to frozen gases [1]. 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 [20]. This procedure is known to remove frozen gases (H₂, CO, CO₂, H₂O) from the cavity surface as well as the RF input coupler surface [21]. Regular partial warm-up to around 50K has been done in DLS to desorb cryosorbed H₂ and CO [22]. Partial warmup to 20K was routinely done at CEBAF after the helium processing [4].

MITIGATION AGAINST FE ONSET DEGRADATION 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 to end the FE onset degradation by control of field emitter particulates and frozen gases. 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:

- Stop the practice of “Hi-potting” ion pumps. Particulate generation from this practice is not proven but it is highly likely.
- 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 [23].
- 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:

- Examine the effect of controlled cryomodule warm-up to a temperature up to 300K.
- Determine the source of field emission degradation during the string assembly and tunnel installation.
• Develop the next generation beamline UHV system.
• Develop a model of particulate transportation.
• 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.

REFERENCES
[14] There is no commonly accepted definition of FE onset in the community. Direct comparison of FE onset reported by different labs should be strongly discouraged, as the present way of FE monitoring is site-dependent. Even within one lab, there may be variations from facility to facility. At Jefferson Lab, the gradient of the first X-ray detection above background is defined as FE onset. Necessary scaling is made for the FE onset at VTA when compared to that at CMTF and onward. For more details, see Ref. [15]. The excellent VTA test results of the 80 CEBAF upgrade 7-cell cavities are reported in Ref. [16].