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UNDERSTANDING AND MITIGATION OF FIELD EMISSION IN CEBAF SRF LINACS*

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Abstract

We present our current understanding of field emission (FE) in two 1.1 GeV continuous wave (CW) superconducting radio frequency (SRF) linacs at CEBAF and its mitigation for improved CEBAF energy reach and operation reliability. We focus on the root causes of FE in operational SRF cavities, including recently installed cavities for CEBAF 12 GeV energy upgrade. We evaluate the effect of initial mitigations implemented since 2016, aimed at reducing generation and transportation of new field emitting particulates. Effects of cavity thermal cycling aimed at abating activation of settled field emitting particulates will be evaluated as well. Remaining issues toward predictable control of field emission in operational SRF cavities will be discussed.

INTRODUCTION

The root-cause studies of FE in CEBAF SRF cavities initiated in 2014 have produced several outcomes. One of them provided unprecedented physical evidence of detecting particulates on the inner surface of an operational SRF cavity with their source being external to that cavity [1,2]. For example, tale-telling Ti/Ta particulates collected from cavities cannot be attributed to sources credibly other than the special differential ion pumps installed in the warm section upstream of a CEBAF-style cryomodule. Other types of common particulates, such as stainless steel, copper, and air-borne “clay” are also observed. Fig. 1 gives examples found on the cavity surface of C50-12 before refurbishment.

An insight has since emerged, namely ***particulate input*** into an operational SRF cavity. This insight drives the formation of a three-step model that governs FE growth over time, the root case for “gradient degradation” in operational CEBAF SRF linacs as established over decades since the early 1990’s:

Particulate generation and inventory from vacuum surfaces including warm beamline components.

Particulate transportation and input into cavities.

Particulate transformation into field emitter in case it lands and settles on high electric field areas.

This model is currently being further improved by gathering more event-driven accelerator operation data as well as offline studies. In this contribution, we will present our current understanding of FE in our operational CEBAF. We will compare the average CEBAF energy loss since 2014, when recently installed cavities for CEBAF 12 GeV energy upgrade began to operate for physics, with that established prior to 2014. We will also evaluate the effect of initial mitigations implemented since 2016, aimed at reducing generation and transportation of new field emitting particulates. Effects of cavity thermal cycling aimed at abating activation of settled field emitting particulates will be evaluated as well. Remaining issues toward predictable control of particulate input and effective removal of settled particulates in operational SRF cavities will be discussed.

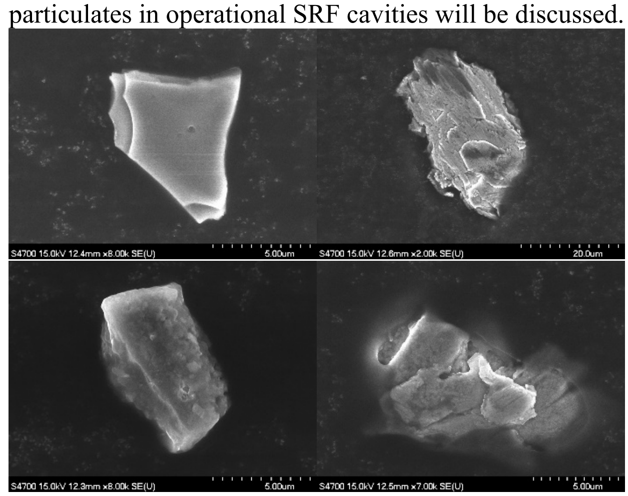

Figure 1: Examples of particulates of Ti/Ta, stainless-steel, air-borne dust aka “clay”, and copper (clock-wise starting at upper left), found on the cavity surface of C50-12 before refurbishment.

CURRENT UNDERSTANDING

Particulate Generation

Detection of Ti/Ta particulates on cavity surfaces as shown in Ref. [1] established beamline ion pumps as one generating source for field emitter particulates.

Two types of ion pumps are used in CEBAF linac UHV beamlines. The first type is a Gamma Vacuum Differential (DI) pump with 50% Ti and 50% Ta electrode elements. One each of this type is attached to the upstream end of a cavity string during the cryomodule assembly process. The second type is a conventional (CV) pump with 100% Ti electrode elements. One each of this second type is installed in the warm girder section between two adjacent cryomodules. In the final tunnel layout, there is one DI pump (aka B pump) upstream of a cryomodule and one CV pump (aka A pump) downstream of the same cryomodule. A good vacuum typically in the range of 10^{-9} Torr is maintained by the B pump in a completed cryomodule at room temperature.

At the point of cool-down, the cavity-string vacuum is generally improved due to cryo-pumping by cold vacuum

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surfaces. It generally is deteriorated over some period of time during cryomodule warmup because of releasing of frozen gases. This kind of vacuum degradation is found to be the case for all cryomodules, but is significantly worse for most C100 cryomodules newly installed for 12 GeV upgrade. Fig. 2 illustrates an example at cryomodule 1L23 (a C100 module) which was isolated from adjacent girders subsequent to the un-planned linac-wide warmup to room temperature. It was triggered by a power outage in cryo-plant CHL1 on July 27, 2017. The vacuum as measured by the upstream ion pump 1L23B ultimately goes up to 10^{-5} Torr range. At such a poor vacuum level, an ion pump is typically shut off (trip) by its control system to avoid violent sputtering. It then remains off till operator initiated recovery. This indeed occurred for most ion pumps following the CHL1 event. But it is not the case for the ion pump 1L23B, as shown in Fig. 2 with greater details in Fig. 2(b): it "self-recovered" quickly following its initial trip and then exhibited repeated cycles of "trip and self-recovery" for many hours.

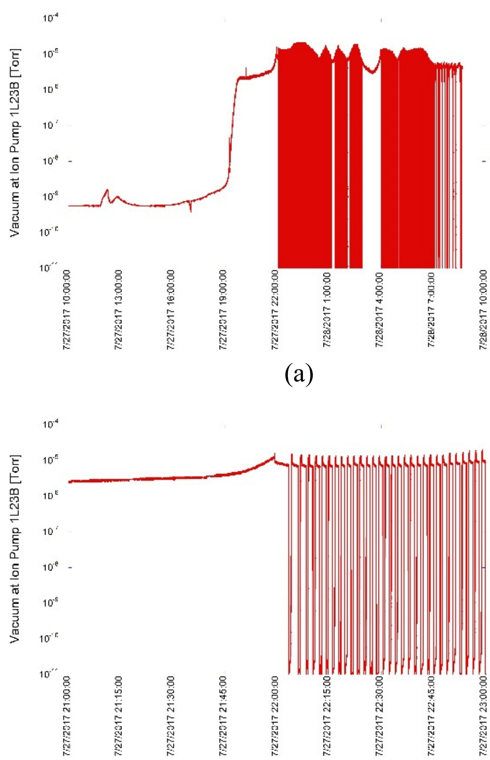

Figure 2: (a) Cavity string vacuum in cryomodule 1L23 following room temperature warm-up with details in (b).

The operational gradient of cavities in cryomodule 1L23 degraded significantly subsequent to the July 2017 CHL1 power outage event (see Fig. 3). The largest loss was observed at the first cavity 1L23-1 in that string. This cavity is closest to the troubled ion pump 1L23B. Similar loss, at a smaller magnitude though, was also observed in cryomodule 1L24 and 1L25 subsequent to another north linac warm-up to an intermediate temperature of 44-170 K, triggered by transformer damage in CHL1 on March 5, 2018. On the contrary, C100 cryomodules without repeated B pump trip and self-recovery during warm-up were found to preserve or improve their gradients. Cavities in C100 cryomodules in the south linac gained on average 0.3 MV/m from warming up to 170-240 K subsequent to the May 5, 2018 CHL1 event. These evidence suggests this mechanism for damaging particulate generation from ion pumps: repeated re-starting at a poor vacuum.

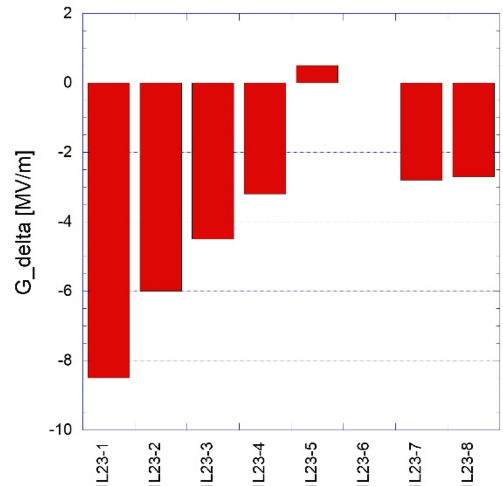

Figure 3: Operational gradient change at cavities in cryomodule 1L23, subsequent to the July 2017 CHL1 power outage event.

Particulate Inventory

Insights gained into particulate inventory from the first particulate collection from cavities in C50-12 before refurbishment [1] led to a change in the standard and procedure for warm girder cleaning and tunnel installation [3,4]. This also opened an opportunity for further collection from not only cavity surfaces but also surfaces of warm girder components. A growing list of inventory particulates has emerged, based on those additional collection from three cryomodules of the same construct as for C50-12 and one C100 cryomodule and warm girder components adjacent to those cryomodule [5,6]. Stainless-steel (bearing elements including Fe, Cr, Ni) and air-borne dust (bearing elements such as Si, Ca, Al, Na, K, and Mg) are consistently observed and dominate the total collected populations. Ag is a unique element found in C100 cavities. It can be now said with confidence that there is a large particulate inventory both on the cavity surface and on the warm girder component surfaces.

It should be mentioned that some of these inventory particulates on cavity surfaces might have arrived before cryomodule placement in the tunnel as shown in Ref. [7].

Particulate Transportation

Besides the indirect evidence from the C20 cavity trip rate analysis [7], we now have two direct evidence in supporting the model of particulate transportation and subsequent input into cavity: (1) Detection of unique ion pump Ti/Ta particulates on cavity surfaces [1]; (2)

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Particulates observed on external warm girder surfaces are also observed on cavity surfaces [5]. In the case of C50-12, Ti/Ta particulates were not only observed at the first cavity in the string, which is nearest to the source ion pump, but also at the last cavity, which is several meters away from the ion pump. This sets the scale of transportation length for Ti/Ta particulates with a size of a few microns.

We are examining the mechanism for particulate input into cavity over long distances. Ordinary mechanical mechanism is not favored as the overwhelming gravitational pull would cause a microscopic particulate to land near its source location. The favored hypothesis is *beam-enabled transportation.* Particulates are initially positively charged due to secondary electron emission when they are irradiation by low energy electrons or X-rays, which are plenty near linacs. They then get levitated and transported by the passing main electron beam, and ultimately are dumped to a new location when the main beam is tripped (which occurs quite often in CEBAF). Preliminary theoretical analysis has establish the feasibility of this transportation mechanism [8]. Experimental studies are to be carried with a special particulate counter currently being prototyped.

Particulate Transformation into Field Emitter

Aided by beam loss monitors, we have observed events linking field emitter activation with frozen gases [9]. This is consistent with the well documented case of dormant particulates being transformed into active field emitters. Gas load analysis has revealed that C100 cryomodules have large frozen gases [10]. In the event of un-planned July 2017 linac-wide room temperature warm up, 2 monolayers of frozen gas was released from a C20/C50 cryomodule on average, whereas 63-100 monolayers from a C100 cryomodule in north and south linac, respectively. Fig. 4 gives the result for all cryomodules in north linac. The result for module with label "T" is only a lower bound as vacuum data became unavailable after B pump was tripped at high vacuum pressures. C100 cryomodules are therefore at a higher risk of particulate transformation into a field emitter arising from frozen gas activation.

MITIGATIONS

Several mitigations have been implemented since summer 2016, aimed at reduction of post-tunnel-installation source particulates:

The practice of "Hi-potting" ion pumps stopped.

Frequency of beamline gate valves cycling reduced by raising pressure threshold for gate valve closure.

New standard and procedure applied to warm girder cleaning and tunnel installation.

New beamline vacuum system based on NEG pumps developed and implementation started [11].

With these implemented mitigations, the current CEBAF average energy loss is held at 35 MeV/yr including the ten newly installed C100 cryomodules since 2014. This is close to the previously established loss of 34 MeV/yr up to 2014. This confirms the benefit of ion pump and gate valve mitigation applied linac-wide. The effect of local mitigations such as girder cleaning and new NEG pumps are not yet so clear, owing to small statistics.

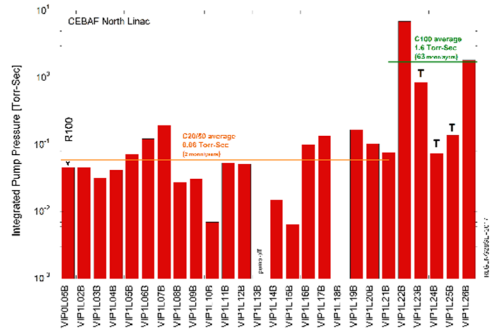

Figure 4: Gas load released from north linac cavities subsequent to room temperature warn up triggered by July 2017 CHL1 power outage.

Based on new understandings, we are implementing new mitigation measures for further reducing source particulates: Shut off B pumps before warming up a C100 cryomodule and evacuate released gases with external turbo pumps. In the meantime, we continue to determine the root cause of large frozen gases in C100 cryomodules.

At this point, our root-cause studies on FE in CEBAF has reached a milestone in establishing particulates as a dominant source field emitters. Our focus now will switch to the development of novel techniques for ***particulate removal*** from a cryomodule in-situ without full module disassembly.

CONCLUSION

In conclusion, new evidence has been presented in support the model of ion pump particulate generation. The large gas load in C100 cryomodules is a major factor leading to the condition of particulate generation in B pumps. Mitigation measures for ion pump and gate valve operation implemented since summer 2016 appear to be effective and the average CEBAF energy loss with the newly installed C100 cryomodules is held at the same level established prior to 2014. New standard and procedure for warm girder cleaning and installation have been applied to seven segments in the north linac. New NEG pumping systems have been implemented in three refurbished cryomodules. All these measures are documented in the CEBAF Performance Plan [12] to be implemented systematically. We are implementing new mitigation measure for further reducing source particulates from ion pumps. We are developing a new concept of liquid nitrogen cleaning for effective particulate removal from a cryomodule in-situ without full module disassembly. A comprehensive approach is required for reducing source particulates, blocking particulate input into cavities, and removing settled particulates from cavities, so as to reverse the CEBAF energy loss. This in turn provide a foundation for improved CEBAF energy reach and operation reliability.

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