

# FIRST ATTEMPT OF AT-CAVITY CRYOGENIC X-RAY DETECTION IN A CEBAF CRYOMODULE FOR FIELD EMISSION MONITORING\*

R.L. Geng<sup>#</sup>, E. Daly, M. Drury, A. Palczewski, JLAB, Newport News, VA 23606, USA

## Abstract

We report on the first result of at-cavity X-ray detection in a CEBAF cryomodule for field emission monitoring. In the 8-cavity cryomodule F100, two silicon diodes were installed near the end flange of each cavity. Each cavity was individually tested during the cryomodule test in JLab's cryomodule test facility. The behaviors of these at-cavity cryogenic X-ray detectors were compared with those of the standard "in air" Geiger-Muller (G-M) tubes. Our initial experiments establish correlation between X-ray response of near diodes and the field emission source cavity in the 8-cavity string. For two out of these eight cavities, we also carried out at-cavity X-ray detection experiments during their vertical testing. The aim is to track field emission behavior uniquely from vertical cavity testing to horizontal cavity testing in the cryomodule. These preliminary results confirmed our expectation and warrant further effort toward the establishment of permanent at-cavity cryogenic X-ray detection for SRF development and operation.

## INTRODUCTION

Field emission is a known mechanism in loading a superconducting radio frequency (SRF) cavity [1-3]. The consequence of field emission can vary, depending on the nature and location of field emitters. In the least harmful scenario, field emitted electrons form a small current and gain little energy from the stored energy in the cavity, therefore there is hardly detectable impact to the quality factor of the cavity, although there might be clearly detectable X-rays by high-sensitivity radiation detectors placed in the vicinity of the cavity. Most of the time however, field emitted electrons form a large enough current and/or gain a high enough energy, resulting in significant impact to the quality factor. Due to the exponential field dependence of the current density, raising the gradient further in this scenario becomes quickly prohibitive as the RF power dissipation is dominated by the process of "accelerating" the unwanted stray electrons. Energetic electrons striking the cavity wall also raise the local cavity wall temperature and eventually may trigger the cavity to quench, setting a hard limit to the attainable gradient. SRF cavities are oftentimes assembled into a long "string" which is in turn embedded in a cryomodule for installation in accelerators. In case of such a long string, electrons field emitted from one cavity

can traverse the full length of the cavity and continue to travel into the next cavity, resulting in high energy stray electrons. When these electrons ultimately get lost from striking cavity walls or beam line components, energetic gamma rays are resulted, which in turn generate neutrons via photo-nuclear reactions [4].

While the body of knowledge about the field emitters inside SRF cavities is well established and avoidance of field emission has been quite successful for individual cavity qualification by applying the state-of-the-art cavity surface processing and handling techniques, there remain some open questions regarding field emission from a successfully qualified cavity to a performing cavity in a cryomodule installed in an accelerator. Notable ones are:

- Why do some cavities degrade in performance due to field emission from single-cavity vertical qualification test to integrated cavity string horizontal test in a cryomodule? Where are the active field emitters located? What is the origin of active field emitters?
- Is it possible to gauge the severity of field emission in a "common language" that is unique to the cavity and independent of the testing facilities?
- Why do new field emitters turn on during beam operation of cavities in CEBAF [5]?

In order to address these questions, a concept of permanent at-cavity cryogenic X-ray detection (ACCD) is introduced. Following the successful validation of X-ray detectors attached to cavities immersed in liquid helium for vertical testing at JLab's VTA facility, we carried out initial experiments of at-cavity X-ray detection during single-cavity qualification tests. We tested the concept in a 8-cavity cryomodule for CEBAF. First results of these efforts are reported in this contribution.

## DETECTOR VALIDATION FROM VERTICAL CAVITY TESTING

Silicon diodes have long been used in the field for cryogenic X-ray instrumentation for field emission studies [6,7]. The Hamamatsu S12230-1 PIN diode has been chosen based on evaluation among several candidates [8]. The same diode has been recently used at JLab for field emitter localization by combining the measured X-ray distribution with the computed electron trajectories [9].

The standard X-ray monitoring for cavity field emission in JLab's VTA facility is realized by placing an ion chamber (Canberra AM-IP 100) in the air at a location outside the cavity vertical testing dewar but within the dewar radiation shield. The distance between the ion chamber and the top flange of a 9-cell ILC cavity is approximately 3 meters. We carried out vertical tests of several different cavities with simultaneous X-ray monitoring by at-cavity cryogenic diodes and in-air ion

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<sup>#</sup>geng@jlab.org

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chambers. The output voltage of the at-cavity diodes is well correlated with the dose rate measured by the in-air ion chambers. The noise level of the at-cavity cryogenic diodes is fairly large, limiting the detection sensitivity when the dose rate is small. Typically, the onset of the diode output voltage corresponds to a dose rate measured by the ion chamber in the range of 1-10 mR/h.

For cavity testing in JLab's VTA facility, X-rays generated by field emission in cavities have always been monitored by the in-air ion chamber. The cavity gradient at which the X-ray dose rate deviates from the background is the traditional definition of the "field emission onset". Because of the relative insensitivity of the diode as compared to the ion chamber, there is a delay (typically a few MV/m) between the field emission onset determined by the ion chamber and by the at-cavity diode (for consistency, we define the gradient at which the diode output deviates from the background as the "field emission onset" determined by the diode). On the other hand, a good correlation is observed between the diode's field emission onset and a knee in the  $Q(E_{acc})$  curve. This observation indicates that the at-cavity diode's field emission onset is a more useful indicator of the added cavity loading due to field emitted electrons. Therefore, one can expect meaningful prediction of field emission onset and loading by the at-cavity cryogenic diodes so as to correlate field emission to the added cryogenic loading.

### AT-CAVITY X-RAY DETECTION IN A FULL-SCALE CEBAF CRYOMODULE

Figure 1 illustrates the 8-cavity string of the F100 cryomodule for CEBAF. Two Hamamatsu S12230-1 PIN diodes are installed per cavity, one at each end beam tube flanges of the 7-cell cavity. The cryomodule cavity testing was carried out in JLab's Cryo-Module Test Facility (CMTF). Standard field emission monitoring G-M tubes were placed outside the cryomodule at various locations

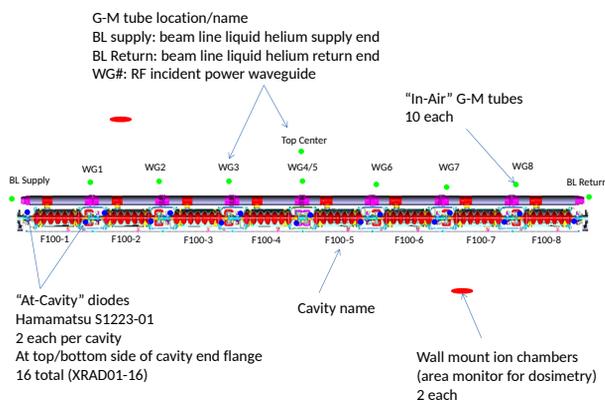


Figure 1: Schematic layout of at-cavity diodes installed in the 8-cavity cryomodule for CEBAF. Two diodes per cavity, one at each end near beam tube flanges.

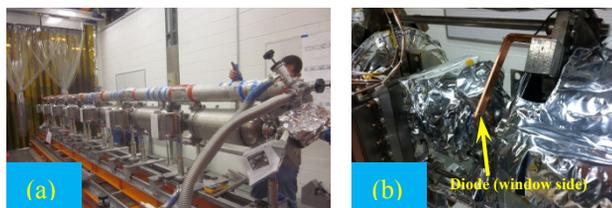


Figure 2: (a) Photo of the 8-cavity string showing the jacketed 7-cell cavities, the rectangular waveguide incident power couplers, and the helium pipe above the cavity string. (b) Detailed view of a diode installed in the F100 cryomodule. The window of the un-shielded diode faces the cavity cells.

as shown in Fig. 1. In total, there are ten G-M tubes placed around the module, one each next to the warm section of the waveguide input RF power coupler and one each near the warm beam lines at the end of the cryomodule. Figure 2 shows a picture of the 8-cavity string parked in the cryomodule assembly area in JLab's Test Lab. The diode is located near the beam tube between the end flange of the cavity and the end dish of the liquid helium vessel. It is held by a copper bracket which is in turn attached to the liquid helium vessel of the cavity. The diodes, when used for field emission monitoring, are at cryogenic temperatures and immersed in the insulation vacuum of the cryomodule. The electronics and data acquisition associated with the diodes send the output voltage of the diodes to the control room, allowing real time monitoring as well as correlation analysis with cavity gradients and dose rate measured by the G-M tubes.

Each cavity was individually powered for performance evaluation and components checking during the CMTF test. Figure 3 gives the example of X-ray count rate measurement data by all G-M tubes when the gradient of cavity F100-6 was raised to its limit at 22 MV/m. All the G-M tubes down-stream of cavity F100-6 registered an X-ray onset at  $\sim 16$  MV/m. At a gradient above 19 MV/m, all the ten G-M tubes recorded X-rays with various count rates. This result demonstrates the high sensitivity of the G-M tubes, an advantage for confirming the appearance of field emission. On the other hand, this implies the G-M tubes may have difficulty in localizing the cavity where the active field emitter resides.

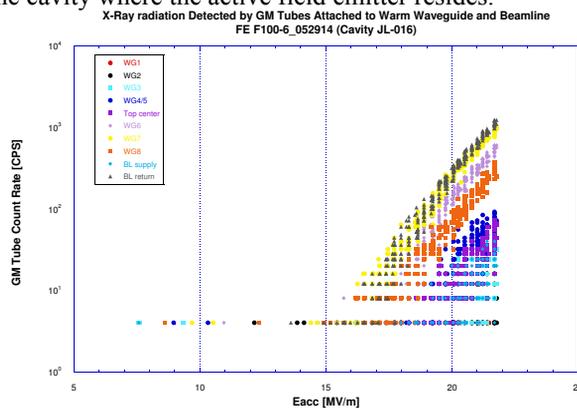


Figure 3: X-ray count rate measured by G-M tubes while the gradient of cavity F100-6 was raised to its limit.

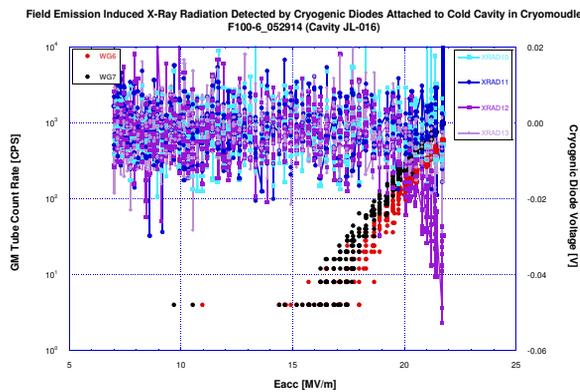


Figure 4: Output voltage of four diodes near cavity F100-6 while its gradient is varied. XRAD11, XRAD12: near cavity end flanges; XRAD10, XRAD13: nearest remote diodes. X-ray count rate signals from G-M tubes (WG6, WG7) are also shown for comparison.

The output voltage signals of four at-cavity diodes near the cavity F100-6 are given in Fig. 4, along with the X-ray count rate signals from two in-air G-M tubes near cavity F100-6. The diode XRAD12 at the down-stream beam tube of cavity F100-6 registered a clear deviation from the background at  $\sim 20$  MV/m, while the other diode XRAD11 installed at the up-stream beam tube of cavity did not show much response. The two nearest remote diodes (XRAD10, XRAD13) did not respond either. None of the far remote diodes showed any response. The field emission onset gradient as determined by the two near in-air G-M tubes is in the range of 16-18 MV/m. The delay between the diode onset gradient and the G-M tube onset gradient is consistent with our early studies comparing the at-cavity diode and in-air ion chambers.

Another experiment was carried out with the gradient of cavity F100-3 raised to its limit of  $\sim 21$  MV/m. In this case, all G-M tubes up-stream of the cavity registered an X-ray onset gradient in the range of 12-14 MV/m. At the limiting gradient, all ten G-M tubes recorded X-rays with various count rates. In contrast, only two diodes between cavity F100-3 and F100-2 registered output signals with an onset gradient in the range of 16-18 MV/m. Two diodes between cavity F100-3 and F100-4 might also show responses, but the signal-to-noise ratio was poor. None of the remote diodes responded.

It should be noted that both the at-cavity diodes and the in-air G-M tubes measured an asymmetry in X-ray intensity from one end of the cavity to the other end. This is consistent with the understanding that there is a dominant field emitter in the cavity and depending on the exact location of the active emitter, the electrons emitted at different RF phase angle tend to travel toward one end flange of the cavity, hence generating an asymmetric striking path over the cavity length [4,8]. A small fraction of electrons will gain higher energy and escape the source cavity and ultimately hit other cavities or even the beam line components at the end of the cavity string. This is the reason for the detection of X-rays by the beam line G-M tubes permitted by their high sensitivity. Due to the

insensitivity, only these diodes near the source cavity show responses while all remote diodes remain silent.

## CONCLUSION AND OUTLOOK

We have carried out the first ACCXD experiment with a full-scale 8-cavity CEBAF cryomodule. It has been demonstrated that only diodes installed at or near the field emission source cavity register an output signal while all remote diodes remain silent. This implies that the at-cavity diodes can be used to determine the field emission source cavity during the beam operation of cryomodules. Some kind of diode shielding might be needed to further limit its response to the “local” cavity. The diode insensitivity results in a delay of a few MV/m in determining the field emission onset, as compared to the standard X-ray monitors in JLab’s vertical test facility (ion chamber) and cryomodule test facility (G-M tube). Such a delay seems to be an advantage as the field emission onset determined by an at-cavity cryogenic diode is fortuitously correlated with the onset of field emission loading in a cavity. Therefore, one can expect meaningful prediction of field emission onset and loading by the at-cavity cryogenic diodes so as to correlate field emission to the added cryogenic loading for operation cavities. Obviously, at-cavity cryogenic diodes can be also used for fast detection of X-rays for SRF accelerator operation and investigation of field emission related fast trips. This will be a future study topic. We also attempted to track field emission by ACCXD from vertical test to cryomodule test but the two cavities studied did not show any field emission during vertical test. We plan to continue this effort in the future.

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