Evaluation of Total Loss Monitors for Cryomodule Radiation Measurement

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Abstract: Operation of high power accelerators presents great challenges for radiation monitoring. For the Advanced Superconducting Test Accelerator (ASTA), radiation is created when there is a beam loss or field emission as long as the cavities are powered at a gradient over 20MV/m. The Total Loss Monitor (TLM) is a radiation monitoring instrument for both beam diagnostics and personnel protection. It has been successfully installed and proved to be working. The TLMs are expected to soon serve as a diagnostic device to detect beam loss over extensive regions in beam line enclosures. However, it is also found out that TLM's sensitivity is relatively low in terms of detecting X-rays due to field emission, and comparison between responses is therefore limited. The paper presents an overview of the design of TLM and an evaluation of its ability and limitations in cryomodule radiation measurement.

I. INTRODUCTION

The Advanced Superconducting Test Accelerator (ASTA) is currently being commissioned at Fermilab. It will support a broad range of beam-based experiments to study fundamental limitations to beam intensity and facilitate further studies relate to particle-beam generation, acceleration, and manipulation. It incorporates a superconducting radiofrequency (SRF) linear accelerator coupled to a photoinjector and a storage ring. Currently, one 1.3 GHz superconducting accelerating cryomodule, CM-2, has been installed immediately downstream of the RF photoinjector, and it is well on the way to become a fully operational cryomodule. After all 8 cavities in CM-2 have been tested individually and could achieve the administrative gradient limit of 31.5 MV/m, the commissioning of the entire cryomodule begins when all the cavities are powered simultaneously by one Klystron.

The Total Loss Monitor (TLM) is a radiation monitoring instrument installed under CM-2. It is considered for use in Radiation Safety Systems at Fermilab to limit the intensity and duration of unintended beam losses over extensive regions in accelerator and beam line enclosures. For ASTA, the TLM is proposed to be used for both beam diagnostics and personnel protection. Because the TLMs are mounted in a way that each chamber corresponds to two cavities, the readings from each electrometer could potentially be used to identify the location of beam loss or radiation to specific cavities. Though the TLM is mainly intended to monitor beam loss, its ability to detect X-ray radiation due to field emission from the cryomodule has also been investigated.

II. TLM DESIGN

A. Comparison with other monitors

At Fermilab, there are other radiation monitors such as 'chipmunks' and 'scarecrows' that have been calibrated with gamma rays source [1]. However, these spot detectors are mainly used for outside thick shielding, and it is very expensive and impractical to adequately cover an entire accelerator with them. Other loss monitors like scintillators have high sensitivity and can measure both the intensity and the energy of the radiation, but they are essentially expensive spot detectors as well. Long Loss Monitors have been used at various laboratories since 1960's for machine protection and diagnostics. However, they are typically uncalibrated devices, and there is no way to check whether the device is functioning or not. Another alternative is using Toroids to measure the charge difference between the upstream and downstream of a beam line to determine beam loss. However, the calibration and measurement accuracies of such device limit the beam loss detection to about 2%, which could still create significant radiation areas in the enclosures. The Total Loss Monitor is not only inexpensive to build, but also able to cover the entire length of the cryomodule and have relatively high accuracy in terms of monitoring the beam loss.

B. Working Mechanism

When there is a beam going through the cryomodule, possible beam loss can lead to electromagnetic showering - the production of a cascade of secondary particles after a high-energy particle hits the cavity wall. Particles including secondary electrons, photons, and neutrons are all generated in the process. Even when there is no beam going through, as long as the cavities are powered at a gradient over 20 MV/m, field emission can happen, generating X-rays. Dark current, electrons emitted from the surface of the accelerating cavities and accelerated along the length of the cryomodule, can be generated as well; it is typically measured only at the ends of the cryomodules.

TLMs are used to detect and measure the ionization radiation by observing the interaction of charged participles with the detector gas in the ion chamber. When a charged particle passes through the detector gas, the gas is ionized, producing ion-electron pairs. The free electrons are then attracted to the center anode so that a small current is generated, and the signal is collected by an electrometer almost immediately.

C. TLM Structure

The TLM design is based on the HJ5-50, HELIAX Standard Air Dielectric Coaxial Cable shown in Figure 1. A bias voltage is applied to the outer shield while the signal is collected from the center conductor. A mixture of 80% argon and 20% CO_2 as the detector gas flows between the outer shield and the center conductor.

FIG. 1. HELIAX Standard Air Dielectric Coaxial Cable

For a TLM, a bias voltage of +800 volts is applied to the outer shield, and a signal cable is attached on the same end of the detector. At the other termination of the detector, a nominal 10 Tera-Ohm (TΩ) heartbeat resistor is connected across the inner and outer conductors. This enforced current flow serves as the heartbeat for the TLM and provides a background signal of 5 nC/min. Since the heartbeat resistors have a 30% tolerance, some variations in the background counting rate are expected.

D. Choice of parameters

Argon gas is chosen as the primary detector gas because its electron attachment rate to form negative ions is very small, which enables all electrons generated to move to the inner conductor instead of hanging on to the argon atoms. The gas choice is optimized by adding some CO_2 to the argon gas. Figure 2 [2] shows the response of TLMs filled with different detector gases to the radiation created when a controlled proton beam was entirely lost. It is demonstrated that the signal response with argon and CO_2 gas is less sensitive to the change in bias voltage than the one with pure argon. It is also found out that, for the same amount of controlled beam loss, with the additional CO_2, the reading on the electrometer will be smaller, creating a desirable larger dynamic range. Last but not least, the mixture of argon and CO_2 is cheaper than pure argon, which lowers the gas cost by about 20 percent.

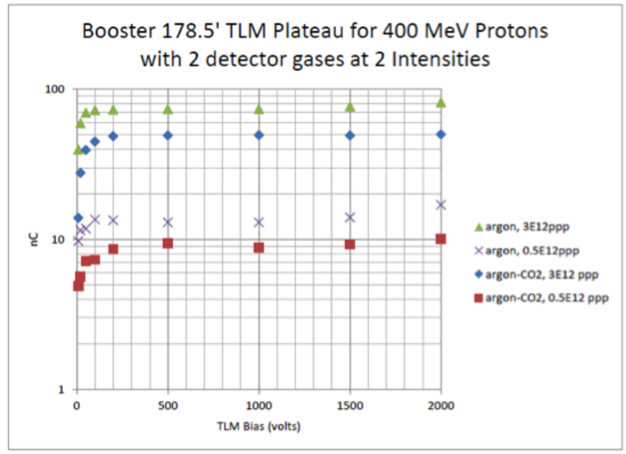

FIG. 2. TLM responses (nC/min) with different bias voltages (volt) and two gas choices at two intensities for 400 MeV protons

The outer shield is designed to be the cathode, while the inner conductor is designed to be the anode, which is also the signal output. In cylindrical ion chambers with the inner conductor having positive polarity, more than 50% of the external signal is due to the motion of the electrons. The polarity is preferred because of the relative drift velocities of electrons and ions. At 1 atm and a gradient of 1000 V/cm in this specific detector gas, the electron drift velocity is about 1000 times faster than that of the positive ions. Thus, when the center electrode is positive, the dominant signal is produced by the electrons with high mobility. This provides a dominant fast external signal while the slow moving ions produce a relatively small external signal.

The bias voltage of +800 volts is a thoughtful choice as well. First of all, the voltage should be far below the threshold of damaging the TLM. In addition to the concern for voltage capacity, the design also takes into account the theories [3] relate to ionization detector regions: the bias needs to be large enough to prevent the recombination of the electrons with their parent ion after the ionization. In this case, the electric field created in the ion chamber needs to be larger than the Coulomb field in the vicinity of the parent ion so that the electrons can escape the initial recombination. The bias pressure should also be small so that it does not fall in a range called the proportional region, when the number of electrons collected at the anode increases with voltage. The biased voltage is optimized to fall in the "ion chamber region" in which exactly one electron reaches the anode when one ionization incident occurs. In other words, there should be no recombination or electron multiplication. The 800 volts bias is selected because it falls in this saturation range, and the signal no longer depends on the voltage applied but only the intensity of the radiation.

E. Monte Carlo Simulation

The Mote Carlo simulation with MARS code is used to predict the TLM response with a given beam loss because it can accurately simulate electromagnetic showering. The showering is a complex process: for an initial high energy photon, pair production happens, which convert photons into an electron-positron pair. High-energy electrons and positrons primarily emit photons through a process called bremsstrahlung. These two processes continues until photons fall below the pair production threshold (1.022 MeV), and then other energy losses of electrons start to dominate, including photoelectric effect and Compton scattering. Thus, the Monte Carlo simulation has to be employed so that billions of low-energy particles could be tracked until they are all stopped in the matter and absorbed. Because all the particles' interaction in matters are taken into account, the structure of the entire facility, the shielding environment, and even details like the inner structure of the TLMs need to be accurately described as input.

Behind the MARS code, the simplified idea is that the amount of energy lost in the TLM chamber could be found with stopping power given in the Bethe-Bloch equation for various incoming particles with different amount of energy in different materials:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\frac{nz^2}{\beta^2}(\frac{e^2}{4\pi\epsilon_0})^2[\ln(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}) - \beta^2]$$

(It is worth noting that this equation cannot be used for energy loss of electrons in thick material due to all the complicated energy loss process described above. That is also why computer simulation is needed for more complicated models.) With the total energy loss in a known volume and the averaged ionization energy, which is the minimum energy needed to create an ion-electron pair in a specific detector gas, the number of ion-electron pair produced in the chamber could be calculated. Then, it could be converted to charge over a period of time for a given intensity, which is in the form of TLM's reading. For example, in Leveling's simulation [4], the worst case is assumed in which a 30 MeV electron beam is lost entirely in the cryomodule. The Monte Carlo simulation reports that 1.23×10^{-13} GeV/cm^3 is lost in the TLM, so the expected TLM response is

$$1.23 \times 10^{-13}\frac{GeV}{\text{cm}^3 \cdot electron} \cdot \frac{6.24 \times 10^{12}\ electrons/sec}{\mu A} \cdot$$

$$5203\ \text{cm}^3 \cdot \frac{ion\ pair}{30eV} \cdot \frac{electron}{ion\ pair} \cdot \frac{coulomb}{6.24 \times 10^{18}\ electrons} \cdot$$

$$\frac{10^9\ eV}{GeV} \cdot \frac{10^9\ nC}{coulomb} \cdot \frac{60\ sec}{min} = 1282\ nC/(min \cdot \mu A)$$

Note that the unspecified beam intensity is taken care of by the unit μA in the result. The simulation result is expected to be the same as the actual reading if the assumed situation happens. Once a favorable comparison of simulation and measurement is established, one can then claim the ability to predict TLM response for a given beam loss condition even when the accelerator and beam loss condition do not exist. The MARS simulation can also give dose calculation results shown in Figure 3 [4]. The result could also be verified with a calibrated scarecrow detector.

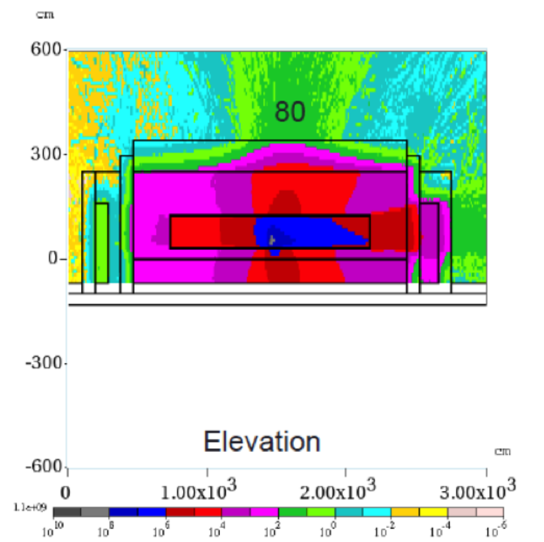

FIG. 3. Total effective dose rate (mrem/hr) given by MARS simulation (elevation view)

However, the X-rays due to field emission cannot easily be simulated because it is difficult to estimate the number of electrons and their energy distribution of the dark current. The only thing we can do is to assume a mono-energetic, mono-directional beam; these simulations are used to predict the worst case challenges to shielding designs. However, it does not give any information for an estimation of the TLM response. To sum up, it is challenging to predict field emission with MARS simulation.

III. CALIBRATION

A calibration for the readout electronics must be developed to interpret the signal. Though the dose rate at any given location could be simulated with the MARS code, it is not meaningful to relate the real signal and the simulated dose rate because the dose rate varies along the length of the TLM while the total charge collected is a single value. The only thing the TLM could give is an average dose rate which is not a practical metric in human dosimetry. One could do a simulation in which a

TLM of fixed length is uniformly irradiated. In this case, the dose rate would be uniform and a total charge could be calculated.

Despite the above reasoning, an estimation has been done to predict the response of the TLM with a calibrated scarecrow. In Figure 4, a 10 inch length of TLM cable was installed in the ASTA cave just downstream of the photoinjector gun which has a gradient of 40 MV/m during operation. The beam is accelerated in the gun and eventually absorbed by a Faraday cup, creating the radiation that two monitors are detecting. Only a small volume of the TLM cable (<5%) is irradiated due to the geometry of the placement of the TLM and the small size of the beam. A scarecrow ion chamber is aligned with the beam just downstream of the TLM cable. The comparison of responses from the two monitors could estimate the strength of a radioactive source that would be required to get a response from a TLM system.

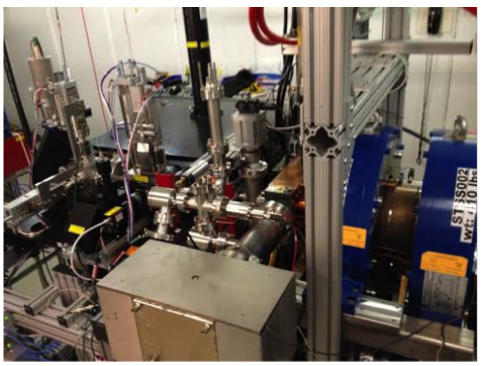

FIG. 4. TLM and scarecrow installed downstream of the electron gun

Low cuts on the data were made to exclude background signal of the TLM (8 cpm) and that of the scarecrow (102 cpm). A low cut was also made on the scarecrow's upper limit at 4000 cpm because the MUX system, a device that sends multiple signals simultaneously in the form of a single, complex signal to another device that later recovers the separate signals at the receiving end, cannot handle data rates greater than 4200 cpm. In Figure 5, the scarecrow is plotted against the TLM (red) and the TLM is plotted against itself (magenta). This proves that the TLM response is linearly correlated with the scarecrow response, at least over the range the scarecrow response is recorded by the MUX system.

In the experiment, 12 cpm TLM response corresponds to a 2400 cpm scarecrow response. The scarecrow and TLM background rates are about 68 and 6.5 cpm, respectively, so the corrected count rates are then about 2330 cpm for the scarecrow and about 5.5 cpm for the TLM. It has been determined that a scarecrow count is 0.025 rem, and the device has a built-in quality factor of 4. Thus, the scarecrow counting rate of 2330 cpm could be converted to 875 mrem/hr, and this dose rate corresponds to 5.5 cpm for the TLM. Therefore, each TLM count is equivalent to about 160 mrem/hr. This experiment shows that a radiative source could be used to source check a TLM detector system, and the conclusion that "each TLM count is about 160 mrem/hr" also enables an estimation and evaluation of the TLM response if the magnitude of the expected radiation is known.

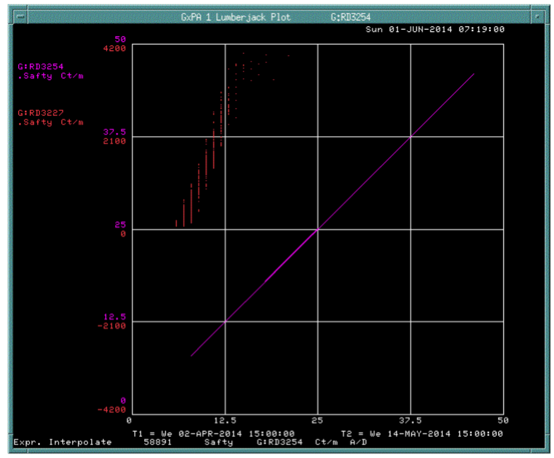

FIG. 5. TLM and scarecrow response (nC/min) without background subtraction

IV. INSTALLATION

Four Total Loss Monitors are installed under the cryomodule and connected as shown in the schematic diagram in Figure 6. The TLMs have a length of 9, 9, 9, and 10 feet, respectively. These lengths were specified to correlate to that of the SRF cavities as the TLMs can be fabricated of virtually any size. Two TLMs (closer to the downstream end of the cryomodule) are connected in series, and together they are connected in parallel with another two TLMs. The reading on the third electrometer should simply be the combined signal from both the third and fourth chambers because it has been proved that the length of the TLM and the way they are connected have no effect on the TLM system performance and the readings from the electrometer. (In Leveling's study [2], the cables were connected in series to determine if the sum of the charge collected from a controlled beam loss is correctly reported at a single electrometer compared to the situation in which the cables were connected in parallel. It is found out that the connection method does not affect the readings.) All four TLMs are aligned and mounted as close as possible to the underside of the cryomodule with 80/20^{TM} aluminum frames. As shown in Figure 7, they are mounted beneath the cryomodule instead of other locations because the accelerating cavities are positioned closer to the bottom inside the cryomodule while cryogenic piping (helium and nitrogen) is located in the upper part of the cryomodule. Gas tubes for the TLMs are also connected, and each connection point is secured.

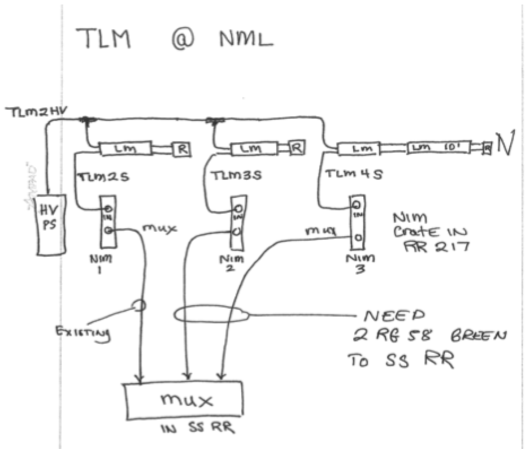

FIG. 6. Schematic diagram of TLMs at NML

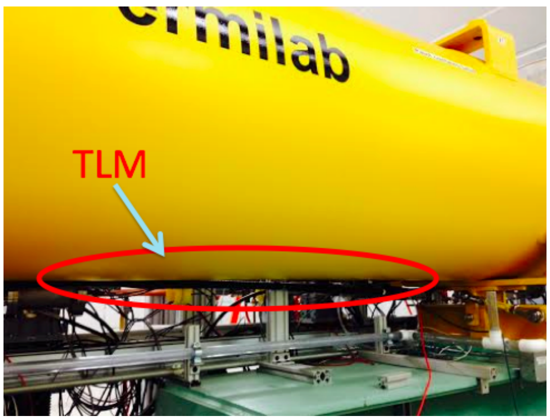

FIG. 7. TLMs installed under the cryomodule

V. MEASUREMENT

It has been proven that a TLM is able to detect significant beam loss according to the source check experiment explained in the calibration section, and the TLMs will soon serve as a diagnostic device to detect the radiation when the beam is on. However, at present, when the entire cryomodule is still under commissioning without beam going through, X-rays are the major source of radiation. In this section, the capability and sensitivity of the TLM to detect field emission is explored.

A. Preparation

Some preliminary measurements were taken before the waveguide distribution system was installed during which the cavities could only be powered and characterized one at a time. However, the results are not informative enough because the chambers were still being purged at that time. As shown in Figure 8, it takes approximately 2 days to have the chambers fully purged. One of the reasons that account for the unexpected reading of 3000 nC/min at the beginning is that, in the chamber, there is some organic gas emitted from the plastic spiral that stabilizes the center conductor. Therefore, the detector gas has to run through the chambers continuously to prevent the built up of polyethylene out-gas poisons.

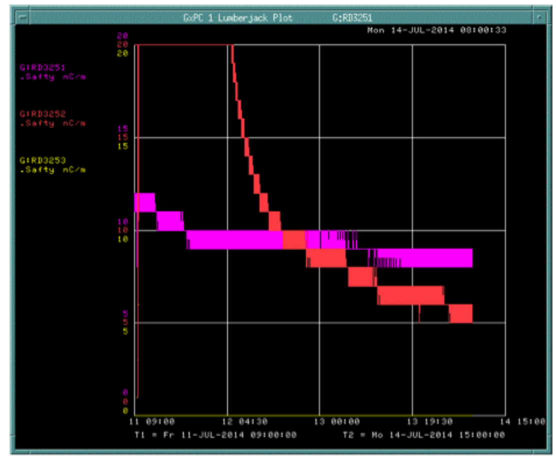

FIG. 8. Response from the TLM (nC/min) in the purge process

B. Radiation measurement

In Figure 9, the TLMs' responses are presented in cyan, magenta, and purple. The yellow curve is the radiation dose rate measured by a scarecrow that is located in the middle of the cryomodule. The green signal is the sum of the gradient in all the cavities, and only 7 out of the 8 cavities were powered when the data was taken. The response of the first TLM (in cyan) is disregarded because it was later found out that there was a bad connection on the SHV Tee that feeds the high voltage.

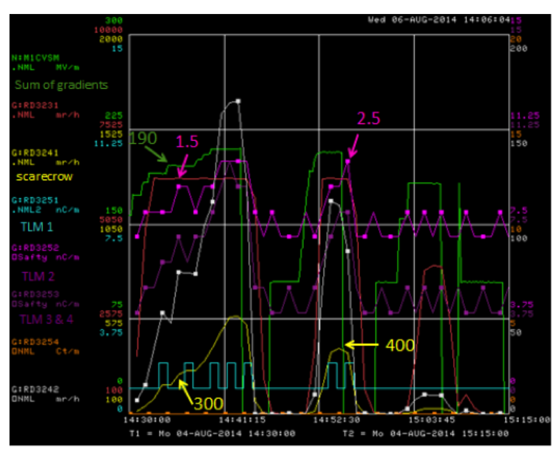

FIG. 9. Responses from the TLMs (nC/min) and scarecrow (mrem/h)

When each cavity was powered at a gradient of 27.1 MV/m (the sum of gradient was 190 MV/m), the TLM-

1 finally detected the radiation with a response of 1.5 counts. At the same time, the scarecrow was detecting the radiation in a dose rate of around 300 mrem/h. This is about 200 mrem/h per count. Same reasoning applies to a second time point, at which the TLM-1's response was 2.5 counts while the scarecrow detected 400 mrem/h. This is about 160 mrem/h per count. Both results are in fairly good agreement with the previous calibration. Note that the scarecrow is located longitudinally in the middle of the cryomodule (a spot between TLM-2 and TLM-3) and vertically higher than where the TLMs are mounted. The radiation at this specific point is not exactly what the TLMs are detecting. Therefore, as long as the results are of the same magnitude, it is reassuring that the TLMs are functioning properly.

Figure 10 is a plot of the radiation detectors' responses as the sum of the gradients increases. The setup is the same as described above except that the bad connection issue in TLM-1 is resolved. In this plot green, red, yellow, and cyan dots are signals from TLM-1, TLM-2, TLM-3&4, and scarecrow, respectively. It is found out the TLMs start to detect radiation at different average gradients: they are 28 MV/m, 27.6 MV/m, and 26.5 MV/m for TLM-1, TLM-2, and TLM-3&4 respectively . For TLM-3&4, the relatively smaller threshold is expected because it is a combined signal from two chambers. However, it is worth noting that, given the gradient calibration errors, these differences are insignificant statistically.

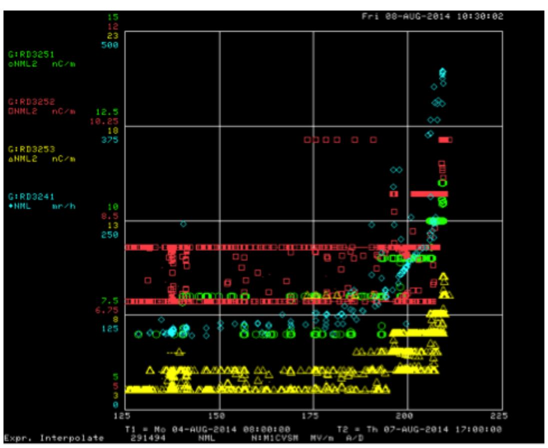

FIG. 10. TLM responses (nC/min) in respect of total cavity gradient (MV/m)

At the maximum average gradient of 30.2 MV/m, TLM-1, TLM-2, and TLM-3&4 had 3.5, 2.5, and 6 counts above background. Still as expected, TLM-3&4 had a larger reading because it was detecting the radiation from 3 operating cavities instead of 2. However, due to the low sensitivity of TLM, the count difference in TLM-1 and TLM-2 does not have a statistical significance. Therefore, it is inconclusive that if the field emission from Cavity-1 and Cavity-2 is really bigger than that from Cavity-3 and Cavity-4.

VI. DISCUSSION

A. Comparison with previous measurement

The response from the TLMs is compared to previous measurements of the X-ray field emission with a scarecrow. Before the waveguide distribution system has been installed, the cavities could only be powered one at a time. Measurements were taken when the scarecrow was positioned right next to the coupler of the powered cavity, which could be considered to be the same location as that of the TLM.

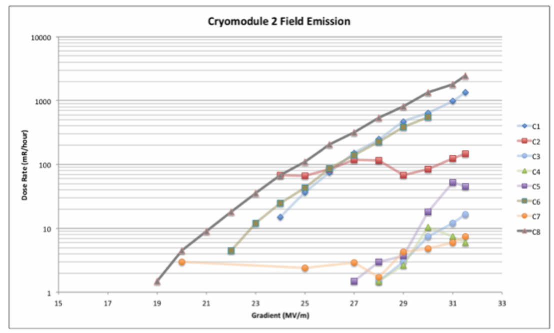

FIG. 11. Field emission (mrem/h) of individually powered cavity measured with scarecrow

According to Figure 11, no response should be expected before the gradient rises up to 26 MV/m because none of the combination radiation (C-1&C-2, C-3&C-4, or C-5&C-6&C-7) exceeds 160 mrem/h at 26 MV/m, and this is consistent with the measurement when all cavities are powered. In Figure 11, at 30 MV/m, for TLM-1, the radiation from Cavity-1 and Cavity-2 is 720 mrem/h, and it is about 4.5 counts if measured by the TLM, which is in fairly good agreement the TLM's actual response of 3.5 counts. For TLM-2, the radiation from Cavity-3 and Cavity-4 is 17.5 mrem/h, which should correspond to no response in the TLM; this is not consistent with the 2.5 counts measured with TLM-2. For TLM-3&4, it is corresponding to Cavity-5, Cavity-6, Cavity-7, and Cavity-8. Since Cavity-8 is not powered, a count of 3.5 is expected because the radiation from the remaining 3 cavities is 575 mrem/h, which also does not agree with the real-time measurement of 6 mrem/h. To sum up, only TLM-1's response is expected.

However, the inconsistency might be due to the discrepancy in gradients when the comparison is made between 30 MV/m and 30.2 MV/m. The radiation dose changes dramatically with gradient because of the exponential increase, especially at high gradient. As shown in Figure 11, an increase of 0.5 MV/m from 30 MV/m could leads to an increase in radiation of as much as 500 mrem/h for just a single cavity (Cavity-1). The uncertainty in the reading could create a huge difference and cannot be overlooked. Moreover, the X-ray emission from each cavity could be different when the nearby cavities are powered, and the showing created from nearby cavities might also be detected. Therefore, further studies are needed to fully understand the X-ray emission when the entire cryomodule is operating.

B. Future work

In the future, adding one more electrometer to separate the signal from the TLM-3 and TLM-4 as well as powering the entire cryomodule including the currently unconnected Cavity-8 should make the readings more comparable to each other. Further studies of the TLMs' response could be done after the gradient is increased further. It is possible to adjust the resonant frequency of each cavity, so another test could be to de-tune cavities and measure TLM response under various cavity powering scenarios. Because the radiation increases exponentially with the gradient, it is possible that, at higher gradient, the difference in the field yield from different cavities may be distinguishable and comparable with the response from the TLMs. In addition, small deviations in the locations of the monitors could affect the comparison as well.

To make the TLM more sensitive, a possible method is to further explore the detector gas choice and gas pressure because a more compact detector gas could potentially increase the TLM's sensitivity. It is also worth investigating that whether or not the calibration only works for electrons with certain energy. Thus, further studies are needed to see if it is reasonable to use the calibration in measurements of X-ray or electrons with much lower or higher energy.

C. Other ways to detect X-ray radiation

As demonstrated in both the calibration and real-time radiation measurement, the TLM is working and could picking up signals from the beam loss radiation and X-ray radiation when the cryomodule is in operation. However, due to its low sensitivity, the response for field emission is not very informative. Therefore, we are looking for other devices that could detect X-ray radiation.

Other than a gas filled ion chamber, a Sodium Iodide Detector could potentially be used to detect X-ray. When radiation interacts with a solid crystal of sodium iodide, a pulse of light is created and then converted to an electrical signal, which gives a reading on the electrometer. The pulse of light is proportional to the amount of light and the energy deposited in the crystal. These detectors can be used with handheld instruments or large stationary radiation monitors [5].

VII. CONCLUSION

The Total Loss Monitor has been successfully installed and proved to be working for ASTA's cryomodule. Good agreement is shown between the responses from the scarecrow and TLMs in both the source check calibration and actual radiation measurement. The success of installing the TLMs also proved the system to be useable for other components of ASTA, and a single long TLM that could cover the entire gun or cryomodule is envisioned to be built and installed in the future. It has been expected and proved that a TLM is able to detect significant beam loss according to both the Monte Carlo simulation and the source check experiment. When there is electron or proton beam going through the cavities, the TLM could soon be fully taken advantage of to perform beam diagnostics and radiation detection. However, TLM's sensitivity is relatively low in terms of detecting X-rays due to field emission, and comparison between responses is therefore limited. More studies are needed to fully understand TLM's response and to improve its sensitivity.

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