Beam Loss Assessment Through Use of Photomultiplier Tubes

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Abstract

Modern accelerators aim to deliver maximal beam current at stable energy with minimal beam loss. Environmental changes, among other factors, can result in increased beam loss and decreased beam throughput, prompting daily retuning of the accelerator. The compact nature of the oldest part of the linear accelerator limits the available beam instrumentation, making beam loss assessment and tuning difficult. Thus, additional devices for beam loss monitoring must be considered.

Photomultiplier tube-based beam loss monitors (BLMs) were installed along the Fermilab drift tube Linac to assess beam loss. Due to noise, the data from the installed photomultiplier tubes was difficult to assess.

After noise reduction and signal analysis, it was found that the signals produced by the photomultiplier tubes in response to beam loss were consistent for a given configuration and therefore a reasonable measure of beam loss. This project lays groundwork for future work in beam loss assessment using photomultiplier tubes, with the automation of the process developed in this project being the next step in this effort.

Background

At Fermilab, the first accelerator in the chain is a linear accelerator referred to as the Linac, which accelerates a H- beam to 400 MeV. The Linac itself is made up of two parts: The Drift Tube Linac (DTL) and the Side-Coupled Linac (SCL). The DTL was installed in the early 1970s, and operates at 201 MHz resonant frequency. The Compared to the SCL, the Drift Tube Linac is severely lacking in instrumentation, with efforts to compensate for this ongoing. As part of these efforts, photomultiplier tubes were installed on either side of the first two drift tubes in the Drift Tube Linac, as shown in Figure 1.

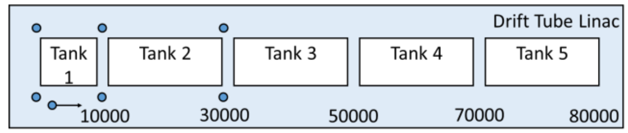

Figure 1: Diagram of the Drift Tube Linac with PMT positions (Circles). The arrow denotes the ability of one PMT to move along a track.

When beam emittance exceeds the accelerator element acceptance in either transverse or longitudinal coordinates, particles from the primary beam hit accelerator structures, producing secondary particles. At low energy (<50 MeV), H- particles hitting copper will produce primarily X-rays. At higher energies nuclear excitation is also non-negligible. Secondary particles propagating through the accelerator elements can then produce further ionizing particle (tertiaries) and so on. Eventually these daughter particles will propagate to the outside of accelerator elements and can be measured as beam loss. The number of detected particles is proportional to the number of primary particles lost.

The newly installed BLMs, shown in Figure 2, are assemblies of a PMT, a plastic scintillator block, and a light guide. Particles hitting the scintillator block will deposit energy, producing light. Depending on the scintillator properties the light can be visible or UV. The Linac BLM assemblies produce visible light, removing the need for a wavelength shifter. The light then travels along light guides to the photocathode of the PMT where it produces electrons through photoelectric conversion. These electrons are focused via an electric field and amplified through a chain of so-called dynodes to produce a sizeable electric current. PMT gain (defined as the number of electrons at the output per one photoelectron) is proportional to the applied high voltage (electric potential) and is typically O(10e6). Altering the input voltage into the photomultiplier tube alters the magnitude of the output signal voltage, allowing for tuning of the signal strength. However, the photomultiplier tubes installed on the Drift Tube Linac are not absolutely calibrated , meaning that beam loss assessed via this method will be based on relative peak size, rather than being based on direct comparison between PMTs.

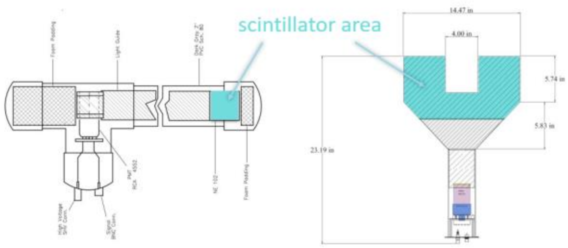

Figure 2: Schematics of the PMT's in use on the Linac. Most mounted PMT's are as described on the left, while the movable PMT is as described on the right.

The PMT response to a single photoelectron is a single peak with a fast rise time (O(5ns)). Therefore the expected signal of the BLM assemblies to beam loss as a function of time is a series of single- or multi-photoelectron peaks coincident with the H- beam pulse passing by the BLM location. To assess beam loss, these fast peaks need to be extracted. Two more contributions to the signal were observed: a distribution of peaks coincident with the RF field in the cavity, but outside of the beam pulse; and a large electronic noise component. The former is interpreted as field emissions being picked up by the BLM. The noise in the output signal complicates peak assessment, requiring processing via hardware and software to remove or at least reduce the noise and detect those peaks after doing so. Much of the electronic noise is due to the 201 MHz RF signal being picked up. Additional noise in the form of ringing in the signal was visually observed on an oscilloscope to correlate with stepping up of the radiofrequency signal as the cavity RF field is being ramped up and down in steps.

It was additionally noted when observing the output signal on an oscilloscope that the output signal massively increases when the toroid signal reports the presence of a beam pulse, matching the expected behavior if the photomultiplier tube is detecting beam loss. Length of beam pulse also correlates as expected with the output signal, with a longer beam pulse producing a similarly longer output signal from the photomultiplier tube.

Methods

Assessment Method Development

Noise reduction in the output signal was the first problem addressed as part of this project, as peak finding on a noisy signal directly output by the beam loss monitor was found to be unreliable, even with hardware processing prior to attempting peak finding. However, the application of a low-pass filter prior to software processing substantially improved the quality of output from the software processing.

Sufficient noise reduction was found to be rather trivial, with the method used for the purposes of this project being to iterate over the waveform, with each data point output by the noise reduction function being the result of multiplying the difference between the current and previous time entry by the product of the current raw data point and the previous raw data point. The net effect of this process is that the difference in time is accounted for in the final signal, reducing the potential impact of measurement time, as well as causing relatively low values to be driven down, with relatively high values being driven up. This causes peaks to be magnified relative to noise, with the graphs on the next column showing the impact of this process on the quality of output signal. Figure 5 also shows the output of the peak finding method, which will be discussed after the graphs.

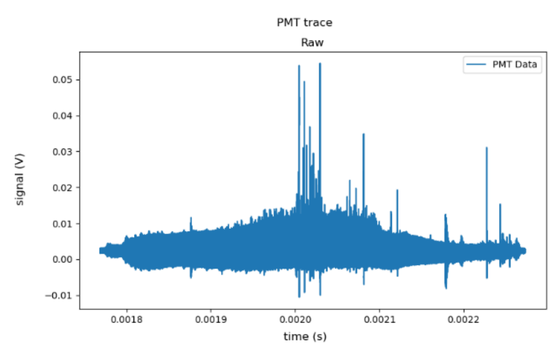

Figure 3: A Waveform Without Hardware Processing

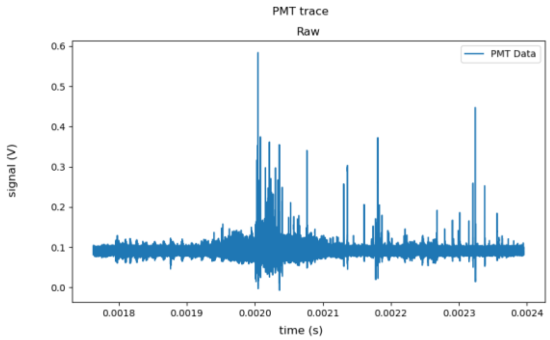

Figure 4: A Waveform with the AC-Coupled Trans-Impedance Amplifier

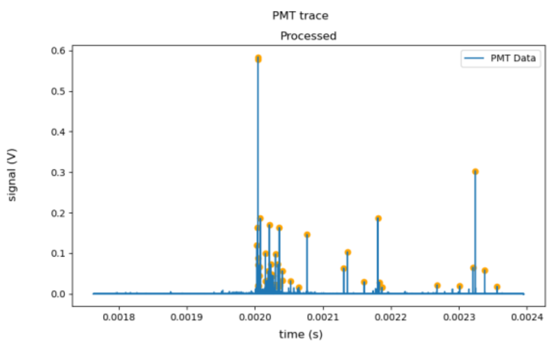

Figure 5: A Waveform with both the AC-Coupled Trans-Impedance Amplifier and Previously Described Software Processing, as well as demonstrating the peak finding described below.

Following implementation of a method of noise reduction, peak finding was assessed. Peak finding was found to also be a relatively simple task, with the Scipy library offering a function for the task. This allowed for peak finding to be a matter of configuration, rather than developing a peak finding algorithm for this project specifically. It was found that most default values were effective for the task, though prominence needed to be tuned to the individual beam loss monitor to detect the desired peaks. Prominence, in this case, is defined as the vertical distance between the peak and its lowest contour line. Additionally, the setting for the width needed to be changed from “None” to “0”. Width determines how much horizontal space a peak much take to be considered and is calculated relative to the prominence of the peak.

Later in the project, peak finding was modified to split the signal into three distinct portions following noise reduction. This was done using the toroid signal, with the signal split along margins based on the value of the toroid signal. When the toroid signal exceeded a configured value, the beam was assumed to be present, and the signal values following that point were placed in a separate waveform list. After the toroid returned to baseline, the beam was assumed to be absent, and the signal values were placed in a third separate waveform list. The peak finding function was then applied to each waveform separately, allowing for much finer control over the configuration of the peak finding based on the presence or absence of a beam pulse. This adjustment massively improved the quality of outputs, making the output more consistent and therefore more useful for later analysis steps.

Beam Loss Study

Once these functions were developed, the Linac beam study period at the end of the regular accelerator run was used to assess beam loss as the beam was tilted using a trim at the start of the Linac. The current through the horizontal trim was varied at 0.2 ampere increments within a range from -1 ampere to +1 ampere relative to the nominal value of 1.152 amperes. For each increment, 5 waveforms from the beam loss monitors were taken using an oscilloscope, which digitized the analog waveform, following hardware processing using an AC-coupled trans-impedance amplifier, and were subsequently processed using the previously described methods.

Results and Analysis

Assessment Method Development

Following peak finding, the peaks then needed to be analyzed to create an assessment of the beam loss based on the peaks found. Though a more sophisticated method could certainly be devised, it was found that simply taking the mean of the peaks’ amplitudes produced consistent values for a given configuration of input voltage and beam pulse signal. Furthermore, this mean was generally positively correlated with higher input voltage, particularly when at 800V or above, as seen in Figure 6. This behavior is likely due to the number and amplitude of the peaks correlating to both the voltage applied to the PMT and the amount of loss. Although summation of peaks was also attempted, it was found to be unreliable as a method of consistent beam loss estimation.

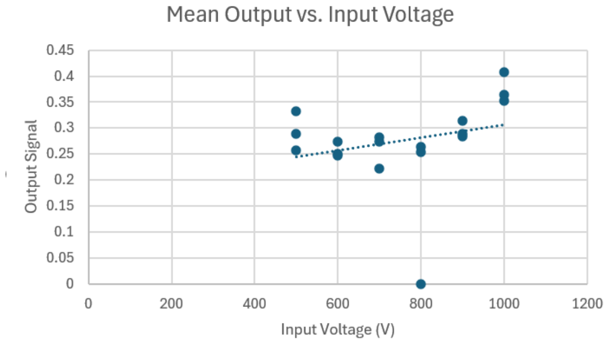

Figure 6: Mean of Peaks vs. Input Voltage

Beam Loss Study

The data taken during the study period showed that the photomultiplier tube which had been run into channel 2 had a positive correlation with the current which was run through the horizontal trim. However, channel 1 did not display the inverse correlation as expected, rather remaining relatively level, as can be seen in Figures 7 and 8.

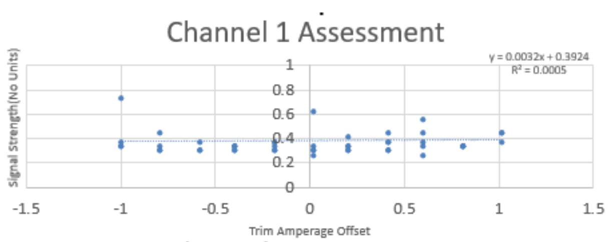

Figure 7: Channel 1 PMT Assessment

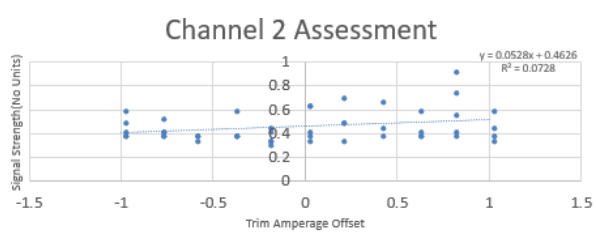

Figure 8: Channel 2 PMT Assessment

Independent radiation monitors showed an increase in radiation detected as the current through the horizontal trim was varied, indicating that the variation was, in fact, increasing beam loss. This was shown both during the experiment itself, when current was varied and measured radiation was assessed to correspond to that variation, as shown in Figure 9, as well as following the experiment, when the data for the time frame during which the experiment took place was graphed alongside the current through the horizontal trim, as shown in Figure 10.

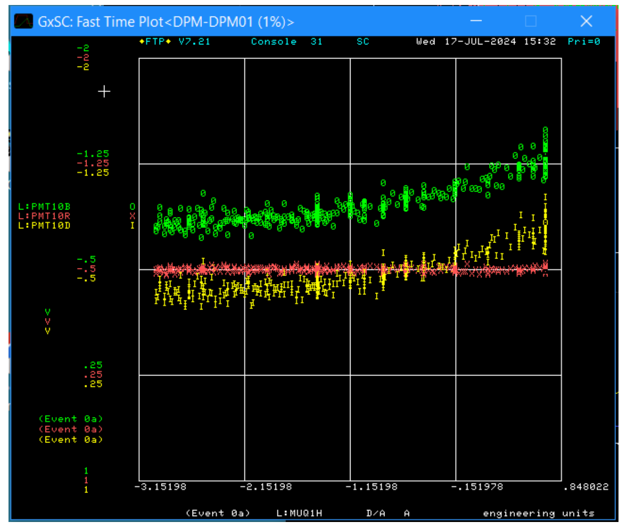

Figure 9: Baseline Radiation (Red), Radiation during beam pulse (Green), and Difference in Radiation Measured (Yellow)

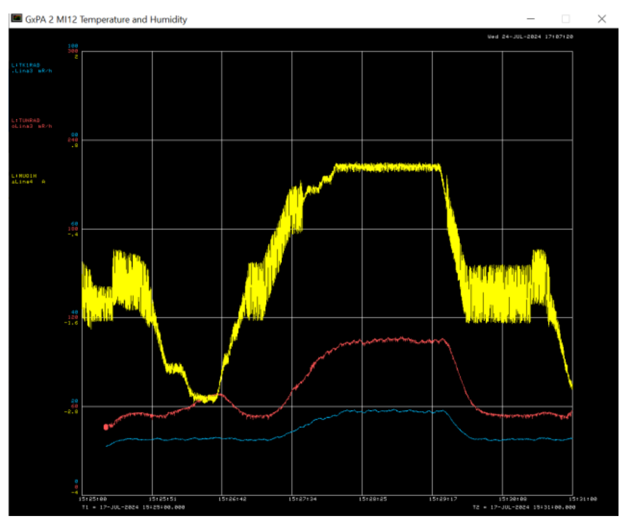

Figure 10: Trim Current (Yellow), Radiation Monitor (Red and Blue)

The reason for the observed behavior of the photomultiplier tubes is unclear, though it does not correspond to the simplified hypothesis that tilting the beam to one side horizontally will primarily increase beam loss on one side of the beam line.. It does, however support the hypothesis that tilting the beam outside of the operational trajectory results in overall increased beam loss.

Conclusion

Within this project, a method to consistently assess beam loss was developed and implemented. Hardware processing was found to substantially improve the results of later loss assessment methods. The methods found within this project can reliably be built off of in future work on beam loss assessment in the Drift Tube Linac, with future work including integration with ACNET to automatically read and process the waveform of beam pulses for analysis of many more beam pulses to assess beam loss estimates over time using this method.

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