

CALCULATING BEAM EXTINCTION IN A PULSED PROTON BEAM USING FPGA-BASED PEAK DETECTION *

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Abstract

The Mu2e experiment at Fermilab imposes stringent requirements on the elimination of out-of-time beam in its pulsed proton beam, a requirement known as “extinction”. Utilizing a new μ TCA-based FPGA data acquisition system, we recorded live particle data from scattered particles incident on an array of quartz Cherenkov radiators and photomultiplier tubes to measure the extinction in the inter-pulse gaps in the pulsed proton beam. Minuscule errors in the derived signal period can make a measurement of the extinction impossible, so after taking a Fourier transform, further optimizations on the period were done based on the assumption that the signal period is stable over the full time of the beam spill while it is being resonantly extracted. After these optimizations, the beam extinction was shown to be on the level of 10^{-3} .

INTRODUCTION

The Mu2e Experiment

The Mu2e experiment requires a pulsed proton beam with a well-defined timing structure and minimal protons present between beam pulses as shown in Fig. 1. The experiment is designed to search for the evidence of lepton flavor violation through the neutrino-less decay of a muon to an electron. Detecting ten signal events in a year would be enough [1].

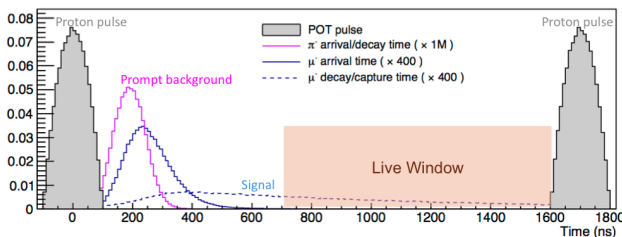


Figure 1: Mu2e uses a proton beam of pulses separated by 1695 nsec with a level of extinction of 10^{-10} between pulses.

Proton pulses are transferred to the experimental hall every 1695 nsec. To ensure clean signal identification, an approximately 995 nsec live signal timing region has been defined between the incoming proton pulses where the desired electron signal can be expected following a 700 ns veto window where background is expected to be the highest. A 5σ discovery requires ≈ 7.5 events against the estimated background of 0.41 over three years.

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Proton Beam Extinction

Mu2e requires the minimization of out-of-time particles between pulses in the proton beam [1]. The beam extinction is defined as the ratio of the number of particles in the inter-pulse time to the nominal pulse intensity (39×10^6 protons per pulse) [2]. The experiment requires the extinction to be less than 10^{-10} [3].

Extinction in the experiment will be achieved in two steps. First, the natural formation of the bunches in the Recycler Ring and Delivery Ring is expected to provide extinction on the order of 10^{-5} . The remaining extinction will be provided by a system of resonant, fast-switching dipole magnets, collectively called the “AC Dipole”, and collimators, configured in such a way that only in-time beam is transmitted to the target and out-of-time beam will be stopped by the collimators. The AC Dipole system will provide an additional extinction factor of approximately 10^{-7} , thus exceeding the required 10^{-10} level [2] by two orders of magnitude.

UPSTREAM EXTINCTION MONITOR

Detector Setup

To obtain an early estimation of beam extinction and to evaluate extinction system performance, an “upstream extinction monitor” system has been installed in the M4 beamline at Fermilab. The detector consists of three quartz Cherenkov radiators and Hamamatsu R7056 photomultiplier tubes (PMTs) arranged in a line, as shown in Fig. 2. They are placed 1 m downstream from a vacuum window and at an angle to intercept scattered particles. The data from scattered beam particles will then be integrated over many beam transfers to obtain an estimate of the extinction.

Insufficient extinction is an accelerator issue that is difficult to amend after the start of data-taking in the experiment, so it is crucial to discover any inadequacies in extinction in



Figure 2: A quartz crystal (25 mm cube) used in the upstream extinction monitor Cherenkov detectors. The quartz crystals are instrumented with PMTs, which have their signals digitized by the FPGA-based data acquisition system.

the beamline as early as possible. The upstream extinction monitor provides a unique opportunity to understand and mitigate unanticipated contributors to the beam extinction before the Mu2e experiment begins to operate.

Data Acquisition System

Voltage signals from each of the PMTs will be digitized by an AD9234 12-bit ADC at a rate of 1 GSPS [4]. These are provided on four Vadatech FMC228 cards assembled across two μ TCA AMC502 cards, allowing up to 16 channels of data to be processed simultaneously. The AMC cards interface with an onboard AMD/Xilinx Kintex-7 series FPGA which performs real-time peak detection analysis, after which it sends peak area, height, and timing information to a local computer via Ethernet. Local analysis on the computer can then be performed to calculate the extinction of the beam. The ability of the FPGA to process data in sub-microsecond times makes it ideal for processing raw data from the PMTs when proton pulses are arriving every 1695 nsec.

DATA ANALYSIS

Initial Plotting Results

Upon receiving real beam data (Figs. 3 and 4), the function of the detectors and data acquisition systems were verified by performing a Fourier transform on the data produced by the FPGA.

With files containing approximately 30 ms of data each, the frequency resolution of a discrete Fourier transform is calculated as the inverse of the time length of the signal, or in this case, $\sigma_f \approx 0.033$ kHz. Alternatively, a shorter time window such as 11 ms ($\sigma_f \approx 0.91$ kHz) is sometimes used to focus on the region with the highest signal-to-noise ratio.

The input to the Fourier transform will be in the form of a noisy Dirac comb, with 95% of particles arriving within ± 53 ns of the nominal pulse center and out-of-time particles in semi-random locations elsewhere through the signal [5].

Fourier Transform Calculation

The Fourier transform revealed that the data obtained from the three detectors had a very clear periodic structure corresponding to the Delivery Ring revolution frequency, with the highest peak in the Fourier transform shown in Fig. 5 as 589.99 kHz (1694.95 ns). For the chosen time window of 4.27 ms, a width of 0.234 kHz is expected for the spectral peak, thus suggesting an initial error proposal of 589.99(23) kHz (1694.95(66) ns), but repeated tests on both simulated data and various real data files show that the actual variation in the measured frequency is much smaller.

A more accurate estimate treats the total uncertainty as the quadrature sum of the Lorentzian-fit error and the CRB term for the frequency variance, given by the formula

$$f_{rms} = \frac{1.219}{\sqrt{T^3(SNR)}} \quad ; \quad t_{rms} = \frac{f_{rms}}{f^2},$$

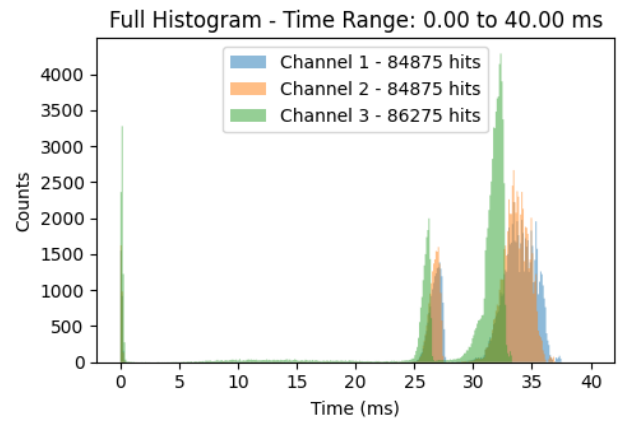


Figure 3: A histogram in log-scale showing the full time profile of one data file. Injection into the Delivery Ring can be seen at 0 ms, and resonant extraction starting at 25 ms. Due to a software limitation, Channel 3 data stops recording data a few milliseconds before Channel 1 and Channel 2.

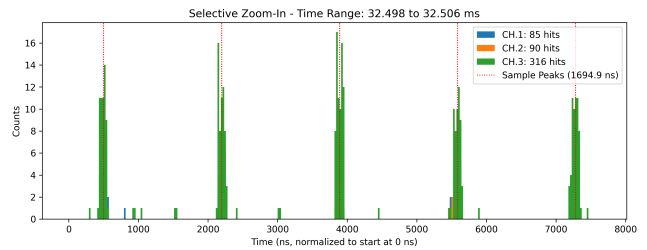


Figure 4: A zoomed-in version of Fig. 3. With red dotted lines to demonstrate a sample ~ 1695 ns periodic signal, it can be clearly seen that the data is of the frequency expected.

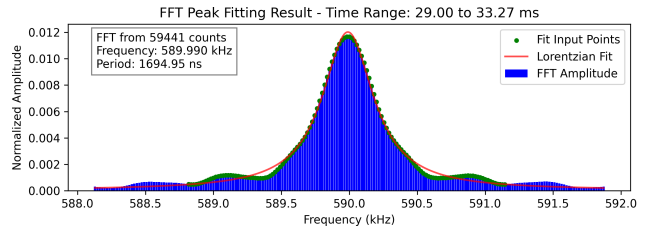


Figure 5: The Fourier transform peak at a frequency of 589.99 kHz (1694.95 ns). It is fitted with a Lorentzian function to further narrow down the exact peak location.

where T is the duration of the input signal (4.27 ms), and SNR is the signal-to-noise ratio of the power of the frequency peak (W) to the noise density outside the peak (W/Hz) [6] (included also is the formula to propagate an uncertainty in frequency to period). Together, these give an error of 0.0016 kHz (0.0046 ns) from the Lorentzian fit and 0.0017 kHz (0.0050 ns) from the CRB.

Taking a weighted average of the periods of all three channels and adding in quadrature the standard error of the mean gives a final value for the period of 1694.9434(44) ns. Repeating the analysis on the full 33.19 ms Dirac comb (including the central region which has a worse signal-to-noise ratio) gives a noisier but thinner spectral peak and a final period of 1694.9449(33) ns.

Correcting the Fourier Transform Period

With the period given by the Fourier transform, the next step to calculating the extinction in the beam is to normalize the times in the data file by the periodicity of the signal to get one single pulse shape. However, the calculated error of 0.0033 ns is too large to make this immediately feasible. In the case of the red trace in Fig. 6, an error of -0.0052 ns accumulated over 37.39 ms (approximately 22,000 cycles of the beam) leading to an incorrect shift in the mean of the plotted post-modulo signal of $(37.39 \text{ ms}/1694.9449 \text{ ns}) * -0.0052 \text{ ns} = -114.7 \text{ ns}$ over the course of the spill.

Therefore, two types of corrections are made to the data.

1. The deviation in the mean value through the spill is used to make a correction to the period, such as in the case above with the -0.0052 ns period correction from the accumulation of -114.7 ns of error.
2. After the period has been corrected, then a constant phase offset is applied to shift the whole impulse train to be centered at zero (168 ns in the case of this data file).

The two corrections are made once, then reapplied a second time using only the central ± 125 ns to avoid being influenced by the tails. The final result is shown in green in Fig. 6.

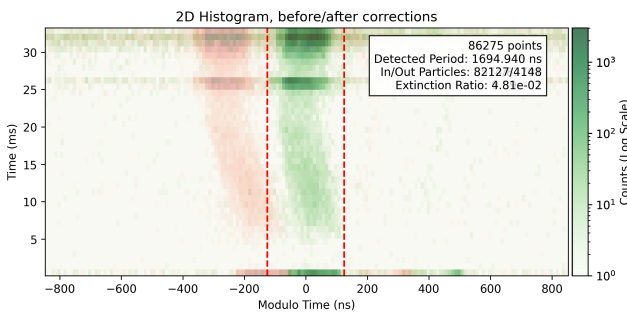


Figure 6: A 2D histogram showing the comparison of the data plotted in Fig. 3 before (red) and after (green) making corrections to the mean and period. The shift leftwards by the original data is likely due to an error in the calculated modulus period rather than a real shift in the beam timing. The dotted red lines at ± 125 ns represents the in-time region for extinction.

Calculating Beam Extinction

With the data in all three channels normalized and adjusted in the form of the green data in Fig. 6, a value for the extinction in the beam can be estimated. Directly, one can take the ratio of the number of particles detected outside ± 125 ns of the beam profile center to the number of particles detected within. Adding the three channels together, there are a total of 250,079 “in-time” particles and 5,946 “out-of-time” particles, corresponding to an extinction of 2.38×10^{-2} .

Lastly, three-fold coincidence events are generated from particles which pass through all three detectors. From the

time window in Fig. 7, the extinction is calculated as 7.40×10^{-3} from 123 out-of-time particles observed compared to the 16,498 in-time particles.

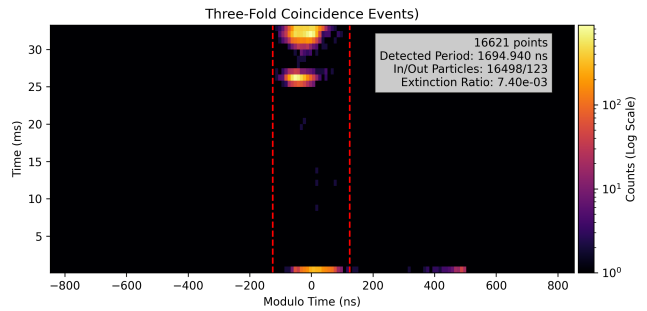


Figure 7: A 2D histogram of three-fold coincidence points. With this condition, the extinction measured in the beam is 7.40×10^{-3} from a ratio of 123 to 16,498 out-of-time to in-time particles.

CONCLUSION

We have developed a μ TCA-based FPGA system to digitize voltage data from a Cherenkov detector array, perform real-time peak detection analysis, and output the results over Ethernet to a local computer for analysis. The detector has been installed in the M4 transfer beamline at Fermilab. Initial plots of the recorded data shows independent phase offsets per channel, as well as a dependence on the modulus period at a higher level of precision than the FFT alone can output given the parameters of this data. After accounting for phase offsets by subtracting the mean from the data and for period errors by subtracting the deviation in the mean per cycle of the pulse, then grouping nearby points from different channels into three-fold coincidence events, extinction could be estimated as 7.40×10^{-3} from 123 out-of-time particles compared to 16,498 in-time particles.

Further Ideas for Progress

- Feeding a known wave into the FPGA and verify the efficiency of the peak detection algorithm.
- Plot a spectrogram of the Fourier frequency over a spill to see if there's any observable and real dependence on event time in the frequency.
- Plot a 2D histogram of Fourier frequencies per event to verify the cross-event stability of the signal and trigger.
- After a delta comb of three-fold coincidence events alone has been generated, re-run the entire Fourier transform and data analysis chain on that three-coincidence-only list and see what kind of result is obtained.

REFERENCES

- [1] L. Bartoszek *et al.*, “Mu2e Technical Design Report”, Tech. Rep. FERMILAB-TM-2594, FERMILAB-DESIGN-2014-01, Fermilab, Batavia, IL, USA, 2014, arXiv:1501.05241 [physics.ins-det]. doi:10.48550/arXiv.1501.05241

- [2] E. Prebys and S. J. Werkema, “Out of Time Beam Extinction in the Mu2e Experiment”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 3996–3999. doi: 10.18429/JACoW-IPAC2015-THPF121
- [3] J. Miller, “Beam extinction requirement for Mu2e”, Mu2e beamline, controls and instrumentation Technical Design Review, Fermi National Accelerator Laboratory, Batavia, Illinois, USA, Oct. 2015, Mu2e-doc-1175, internal report, 2010. <https://indico.fnal.gov/event/10361/attachments/1463/1695/BeamExtinctionRequirementForMu2e-140618.pdf>
- [4] R. Hensley *et al.*, “Extinction monitoring of pulsed proton beams using FPGA-based peak detection”, presented at IPAC’25, Taipei, Taiwan, Jun. 2025, paper THPM091, to be published in the proceedings.
- [5] S. Werkema, “Mu2e proton beam longitudinal structure”, Mu2e-doc-2771, Internal Rep., Fermilab, Batavia, IL, USA, 2019. <https://mu2e-docdb.fnal.gov>
- [6] D. Boschen. “Error estimation for frequency”. Answer confirming $f_{\text{rms}} = 1.219/\sqrt{T^3(SNR)}$, <https://dsp.stackexchange.com/a/78926>