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STATISTICAL MEASUREMENT OF LONGITUDINAL BEAM HALO IN THE FERMILAB RECYCLER*

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Abstract

The formation of non-Gaussian halo in both the transverse and longitudinal dimensions of beam bunches has been notoriously difficult both to model and to measure. We present a technique to measure the longitudinal halo of 2.5 MHz bunches in the Fermilab Recycler, which have been formed for the g-2 anomalous magnetic moment experiment. While out-of-time beam is not a particular concern to this experiment, it is a key issue for the subsequent Mu2e rare muon decay experiment, which will use the same bunch formation procedure. Our measurement relies on a statistical technique, in which a small fraction of the beam is scattered from the primary collimation foil in the Recycler, and then is detected by a charge telescope consisting of quartz Cherenkov radiators and photomultiplier tubes. By integrating over many revolutions, the time profile of longitudinal halo (out-of-time beam) can be measured down to less than a 10^{-5} fractional level, relative to in-time beam. These results can then be compared to simulations.

INTRODUCTION

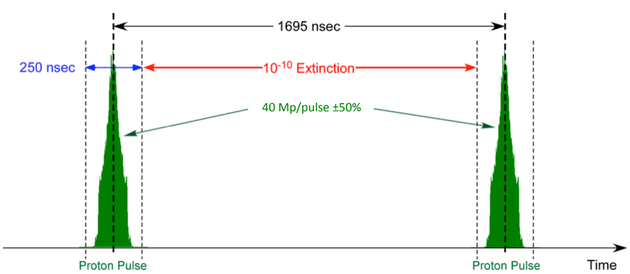

Figure 1: Bunch structure for the Mu2e experiment at Fermilab. The experiment requires that no beam be present between bunches at the 10^{-10} fractional level. This is referred to as the “extinction requirement".

Numerous experiments rely on the precise knowledge of beam halo in the non-Gaussian tails, both longitudinally and transversely. In particular, out-of-time beam in intense beams is lost when the beam accelerates. For example, at Fermilab, residual activation in the Main Injector is already an issue, and it will become far more important as the intensity is increased in the coming years. Other experiments have their own stringent limits on out-of-time beam. Figure 1 shows the bunch structure requirement for the Mu2e Experiment at Fermilab [1], which requires that the fraction of out-of-time beam be less than 10^{-10}. This requirement is referred to as “extinction". The full technique for achieving this challenging specification is described elsewhere [2], but it requires that every step in the bunch formation perform according to plan.

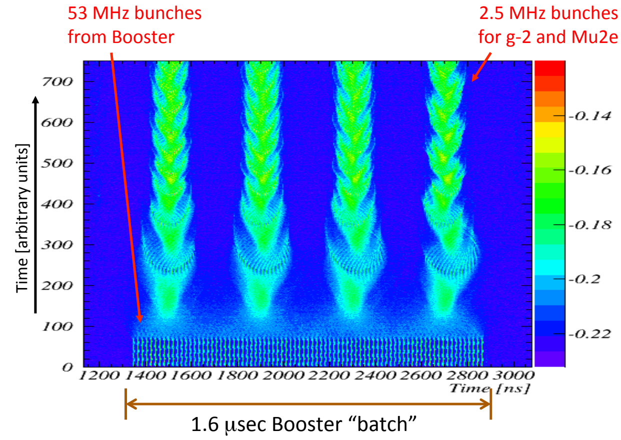

Figure 2: Waterfall plot of the formation of 2.5 MHz bunches in the Fermilab Recycler, starting with 8 GeV 53 MHz bunches from the Fermilab Booster at the bottom. The total time for bunch formation is about 90 ms.

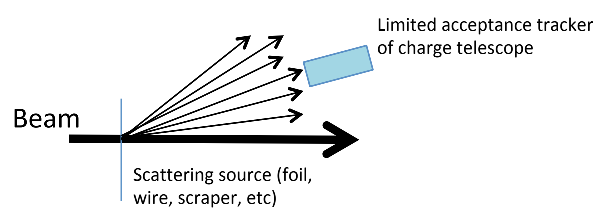

Figure 3: Conceptual illustration of the statistical measurement of longitudinal bunch structure. A scattering source scatters a small fraction of the beam into a tracker or charge telescope, such that an accurate time profile can be built up without introducing saturation effects.

In particular, the first step in bunch formation for Mu2e is to transfer 8 GeV proton beam from the Fermilab Booster Synchrotron to the Fermilab Recycler storage ring, where it will be re-bunched to 2.5 MHz bunches, as illustrated in Fig. 2. In order for the ultimate goal of of 10^{-10} extinction,

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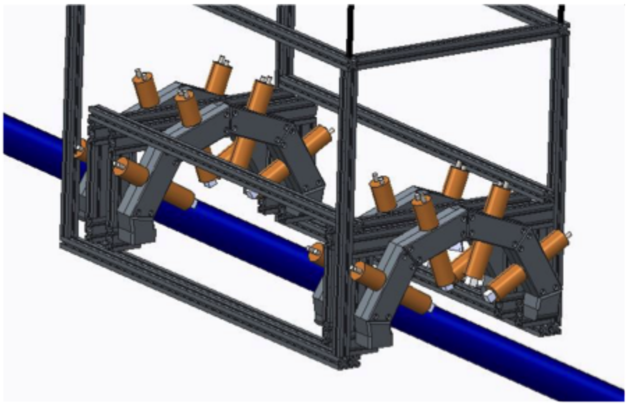

Figure 4: Complete design Precision Time Profile Monitor (PTPM) assembly.

it's necessary for the bunch formation in the Recycler to achieve an extinction of roughly 10^{-5} or better. Simulations show this should be possible, but given the dependence of the experiment on this specification, it's important that we verify it experimentally.

The g-2 Experiment [3], currently running at Fermilab, uses the same bunch formation technique in the Recycler. They do not have the same requirement as Mu2e, but studying the time profile of the bunches during g-2 operation will verify that they are of sufficient quality for the Mu2e Experiment, which is scheduled to follow g-2 in the early 2020s.

Measuring beam halo at this level is very challenging because of the large dynamic range required. Transverse measurement devices can in principle be segmented, such that certain channels, or even all the channels, only probe the beam halo; however, this is generally not possible for longitudinal halo measurement. Traditional longitudinal profile measuring devices, such as resistive wall monitors, typically have a resolution for out-of-time beam at the 10^{-3} level at best. A detector sensitive enough to see small levels of out-of-time beam will generally be saturated by the in time signal, which can lead to ringing, after pulsing, and dead time. Other attempts to measure out-of-time beam involve "blinding" the detector to in time beam, for example by using gated photomultiplier tubes; however, this can lead to problems with absolute calibration.

On the other hand, if the beam is known to have a periodic structure, then statistical techniques can be employed to build a very precise distribution over multiple bunches, as illustrated in Fig. 3 The general idea employs some obstruction in the beam path to scatter a very small fraction of the beam, which is detected by an external detector. This detector should have its acceptance tuned in such a way that beam scattered from the in-time bunches will not saturate it. The details of the detector are not important. The key requirements are:

- It must have a time resolution which is short compared to the nominal bunch length
- It must have a low background fake rate

The latter, along with the maximum integration time, give the limit of the sensitivity of the device.

Similar techniques have been used in the past to measure both transverse and longitudinal halo [4]. Our development is distinguished by its simplicity and portability. The portability of the device makes it useful for a wide range applications at Fermilab. For example, it could be used to measure the out-of-time beam in the 53 MHz bunches in the Main Injector, which is related to beam loss, and therefore has important implications for the entire Intensity Frontier Program.

EXPERIMENTAL TECHNIQUE

Full Implementation

Figure 4 shows the full design for the "Precision Time Profile Monitor" (PTPM), which will ultimately be used in the Mu2e beam line to monitor the extinction in beam being delivered to the experiment. In that implementation, thin foil profile monitors will be used as the scattering source. It is a charged particle telescope comprised of four arms, each with four quartz Cherenkov radiators attached to photomultiplier tubes. Cherenkov radiators are used because they are less sensitive to soft background than scintillator, and they are also less prone to after-pulsing.

Figure 5 shows a representation of the data acquisition for the system, as it will be implemented in the Mu2e Experiment. It's based on the MicroTCA standard [5], implemented with hardware from VadaTech, Inc [6]. The 16 channels of the system will be read out using two carrier modules, with two four-channel 1 Gs/s digitizers each. An onboard Xilinx Kintex-7 FPGA will be configured to perform a peak-finding algorithm on the signals, and then pass the list of timestamped peaks to the data acquisition system via a PCIe dataway followed by a gigabit ethernet link.

Recycler Implementation

As a first test of the system, and to validate the simulations of bunch formation, one arm of the detector has been installed in the Recycler, as shown in Fig. 6. This uses the primary collimator of the Recycler collimator system as a scatterer. The four channels are connected in parallel to both the MicroTCA data acquisition sy tem and a 500 MHz oscilloscope, read out via a VXI11 interface.

As a proof of concept, the oscilloscope was used to read out complete waveforms immediately after injection of the beam from the Booster. These waveforms were then analyzed using a simple peak finding algorithm. These results are shown in Fig. 7, clearly showing the 53 MHz bunch structure.

STATUS AND PLANS

Figure 8 shows the first traces of coincident signals in all four radiators read out by the VadaTech digitizers using the data acquisition path. Because the goal is to measure the

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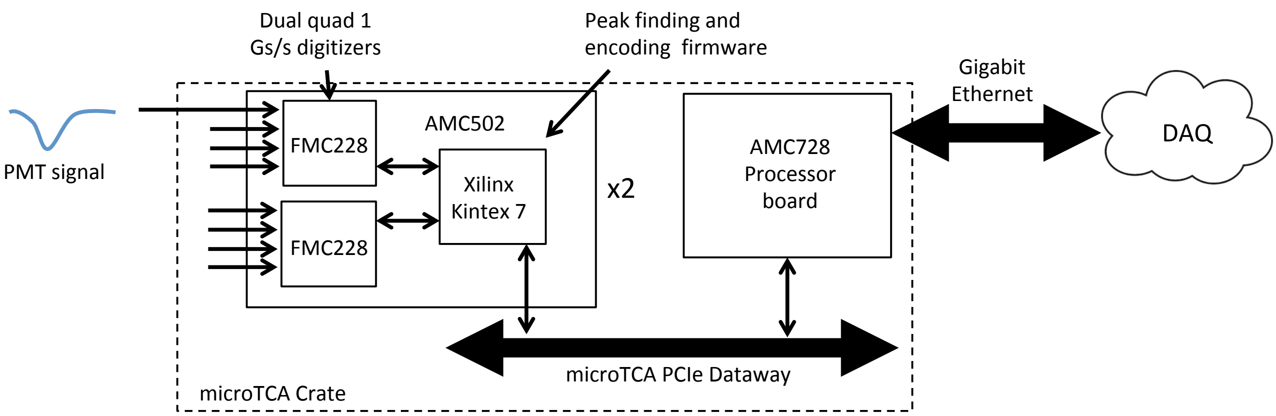

Figure 5: Schematic view of data acquisition system, based on VadaTech MicroTCA hardware. Two AMC502 carrier board are equipped with two four channel 1 Gs/s digitizer mezzanine cards each, for a total of 16 channels. A Xilinx Kintex-7 FPGA will be configured to find and time stamp peaks from each channel. The resulting hit lists will be transfered via PCIe to an AMC728 processor module, which will format it and pass it to the data acquisition system.

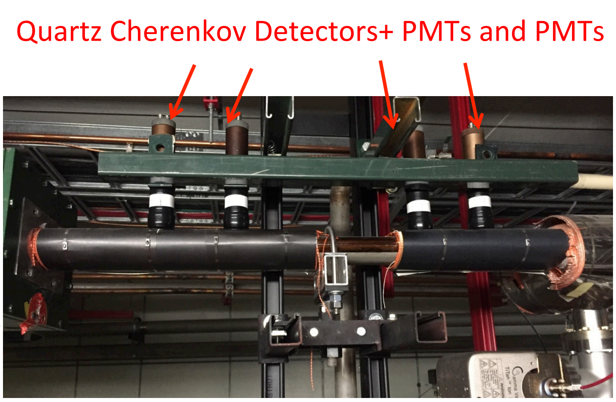

Figure 6: Four radiator counting arm currently installed in Fermilab Recycler.

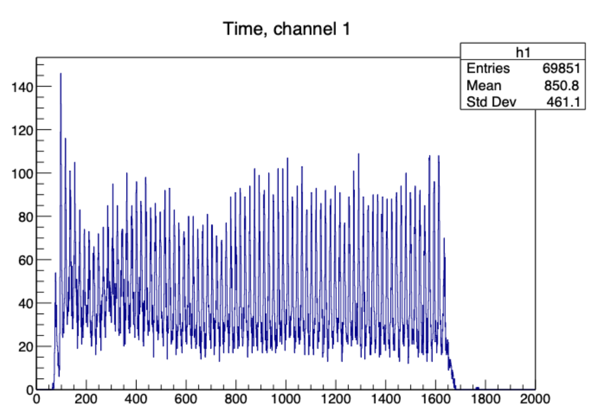

Figure 7: First results from Recycler monitor, showing 53 MHz bunch structure of injected beam from Fermilab Booster, before rebunching. These data were taken using an oscilloscope via a VXI11 interface.

development of the bunches throughout the bunch formation cycle, acquiring full waveforms is no longer practical, so

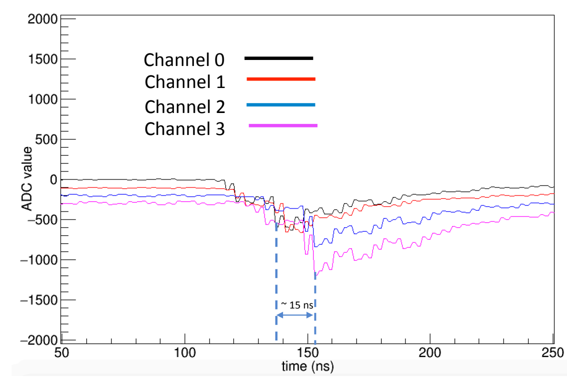

Figure 8: First data from VadaTech FMC228 digitizer module.

efforts now are focusing on development of the pack finding algorithm that will be implemented in the firmware of the FPGA.

It's planned that timing data will be taken on the bunch formation in the Recycler over the next two years, after which the complete time profile monitor will be relocated to the Mu2e beam line to be used in the commissioning of beam for the experiment.

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