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A Schottky Tune Meter for the Fermilab Mu2E Delivery Ring*

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Abstract

The Mu2E experiment will measure the ratio of the rate of the neutrinoless, coherent conversion of muons into electrons as a measure of Charged Lepton Flavor Violation. As part of the Mu2E experiment, a proton storage ring, called the Delivery Ring, will utilize resonant extraction to slow-spill protons to the experiment. To regulate and optimize the Delivery Ring resonant extraction process, a fast tune measurement scheme will be required. This Mu2E tune meter will measure the average tune and the tune spectrum, in multiple time slices, through the entire resonant extraction cycle of nominally 43 msec. The Mu2E tune meter system utilizes vertical and horizontal 21.4 MHz Schottky detector resonant pickups, taken from the decommissioned Tevatron, high-gain amplifiers and digital down-conversion FPGA logic for its signal processing. This paper will present the design of this Schottky tune meter as well as tune measurements from the Mu2E delivery ring.

MU2E SLOW SPILL

The Mu2E experiment will search for the charged-lepton flavor violating process $\mu^- N \rightarrow e^- N$ [1]. Mu2E proposes to measure the ratio of the rate of the neutrino-less, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus. This requires the resonant extraction of a stream of pulsed beam, comprised of short micro-bunches (pulses) from the Delivery Ring (DR) to the Mu2e target [2].

Mu2e uses 8 kW of 8 GeV protons extracted from the Fermilab Booster. Figure 1 show a table of key DR beam parameters. Once 1e12 protons are injected into the DR, beam is then slow extracted to the Muon proton target at the DR revolution frequency of 590.08 kHz over a nominally 43 ms spill period. Between each spill period, there is 5 ms reset period, in which there is no extraction. After the 8th spill, there is no beam in DR for 1.02 s. Figure 2 shows the Mu2E DR intensity timeline for eight slow spills.

By exciting two families of the harmonic sextupoles in the DR, the third integer slow-spill resonant extraction condition is established [3]. Figure 3 shows the modelled change in the DR tune along a single slow spill along with expected data points from this tune meter system.

MU2E TUNE METER SYSTEM

The Mu2E tune meter system, shown in figure 4, consists of 21.4 MHz inductively resonated stripline pickups, low noise RF amplifiers, bandpass filters and a high-speed FPGA-based DAQ board.

Parameter	Value	Units
MI Cycle time	1.333	sec
Number of spills per MI cycle	8	
Duration of each spill	34-54	msec
Number of protons per micro-pulse	$(3.0\text{-}5.0)\times10^7$	protons
Maximum DR Beam Intensity	1.0×10^{12}	protons
Reset Time Gap between spills	5	msec
Operation point (Qx/Qy)	9.650/9.735	
DR revolution frequency	590.018	kHz

Figure 1: Mu2E delivery ring beam parameters.

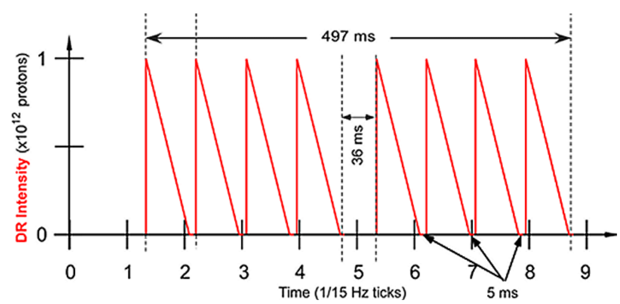

Figure 2: Mu2E slow spill beam timeline.

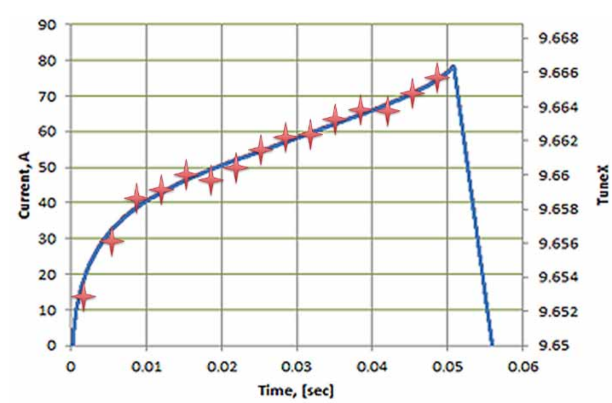

Figure 3: Expected tune along slow spill.

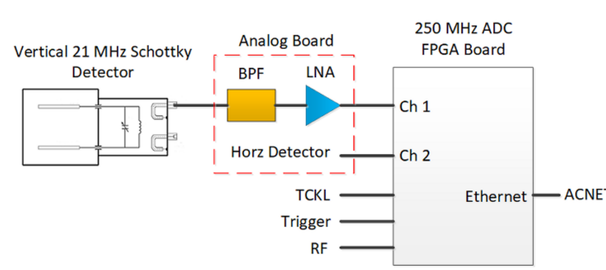

Figure 4: Mu2E tune meter system.

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The system requires low noise RF amplifiers with +80db gain. Crystal bandpass filters are used to suppress the revolution harmonics of the DR. A high-speed FPGA-based DAQ board to use for the digital signal processing.

21.4 MHz Schottky Pickups

Inductively resonated, balanced stripline pickups were used to observe tunes in the now decommissioned Tevatron accelerator [4]. These 21.4 MHz Schottky resonant pickups are now being reused for the Mu2E DR. The Schottky detectors are 1 m striplines consisting of two copper bars which can be moved by stepper motors to change the sensitivity. Its resonant frequency can also be tuned by using the variable capacitor Cv. Presently these detectors are tuned to resonate around 21.4 MHz with a loaded QL = 370 [5]. Two of the Schottky detectors, one vertical and one horizontal, were installed in the Mu2E DR. Figure 5 shows photos of the vertical Schottky pickup.

The DR revolution frequency is 590.018 kHz. The 21.4 MHz resonate frequency of these Schottky detectors then requires us to look for the DR tune lines between the 36th and 37th harmonics of the DR revolution frequency. Figure 6 shows the vertical and horizontal tunes lines between the 36th and 37th harmonics. This figure also shows the frequency responses of both vertical and horizontal Schottky detectors, tuned to optimized sensitivity to their respective tune lines, as well as the bandpass filter widths.

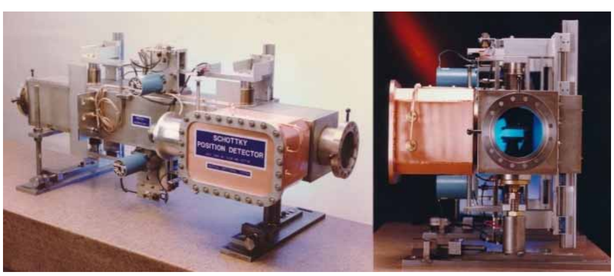

Figure 5: 21.4 MHz resonant Schottky pickups.

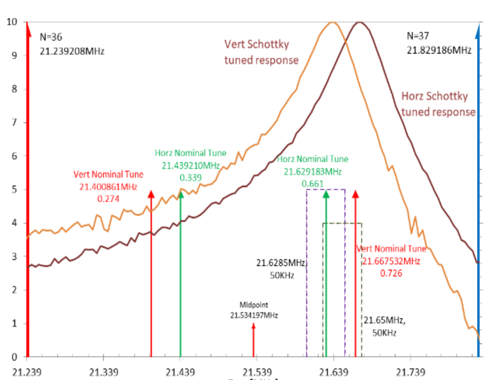

Figure 6: Schottky pickup response and tune spectrum at 21.4 MHz.

Digital Signal Processing

The Mu2E tune meter systems uses a high-speed FPGA VME board that was originally designed as part of a digital damper system for proton storage rings. This board consists of four 16-bit, 250MSPS ADCs, four 16-bit 250MSPS DACs and a Cyclone V FPGA. The present tune meter system utilizes two of the ADC channels for the vertical and horizontal Schottky signals. The FPGA logic digitally down converts the tunes at the 36th harmonic down to baseband. The down converted data is then either analyzed in the FPGA to generate FFT spectrums or else is offloaded to a local computer to further analysis. Figure 7 shows a block diagram of the FPGA logic for down conversion.

The signal processing analysis can time slice the down converted data to generate FFTs along the slow spill. The system can select the number of time slices and whether to average the time sliced FFT across many slow spills to help reduce noise fluctuations in the FFT spectrum.

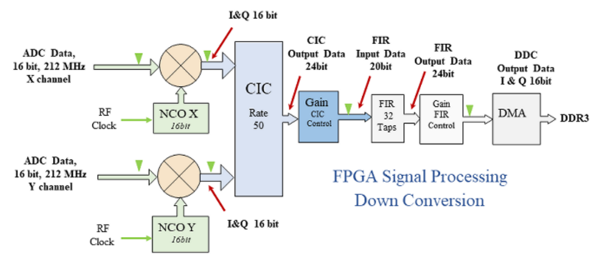

Figure 7: Block diagram of tune digital signal processing.

INITIAL RESULTS

The Mu2E tune meter system has been tested during initial commissioning of the Mu2E DR. Initial tune measurements were made with a spectrum analyzer in place of our FPGA board. This allowed for us to confirm the analog portion of the tune meter with a slower system. Figure 8 show the vertical tune line, along with the bandpass filter width, for ~5e10 protons coasting in the DR.

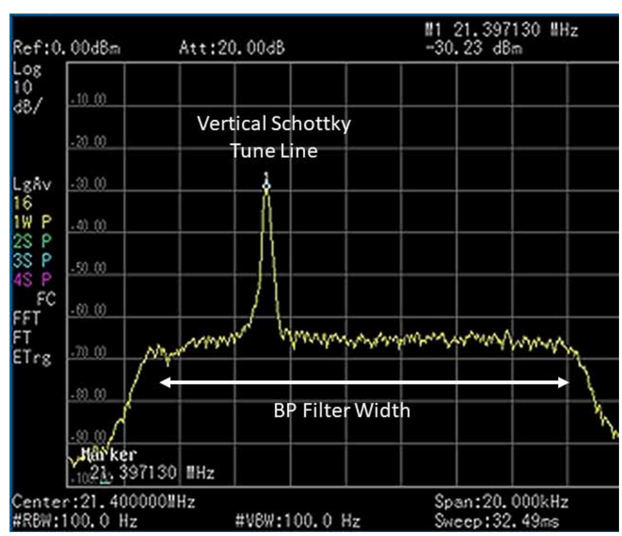

Figure 8: Coasting DR tune taken with spectrum analyzer.

After initial measurements, the spectrum analyzer was replaced with our digital FPGA board. We tested the board operation with millisecond time slices. Figure 9 shows a preliminary measure of the tune spectrum at injection of ~1e11 protons into the DR. This shows the potential of measuring the tune along the slow spill at a few millisecond resolution.

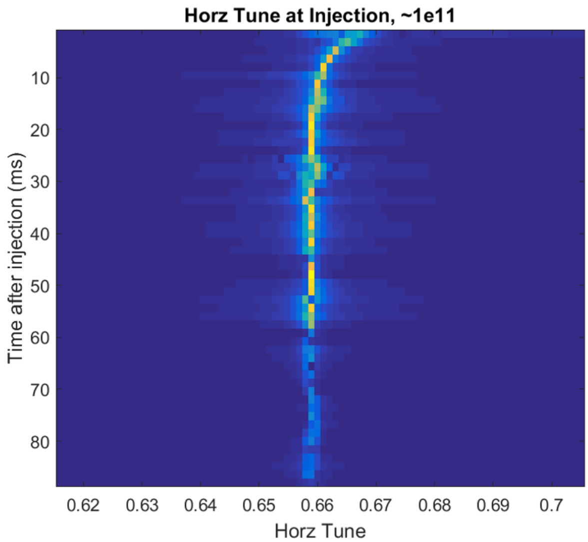

Figure 9: Preliminary DR tune measurements with Mu2E tune meter at beam injection.

CONCLUSION

A Schottky digital tune monitor system, based on 21.4 MHz resonant stripline pickups, has been design, installed and tested in the MU2E DR. Initial tune measurements show that beam tunes can be measured during the proposed Mu2E slow spill time at the time resolution of a few milliseconds. Future beam measurements will focus on measuring these tunes during a slow spill over the full dynamic intensity range in the DR.

ACKNOWLEDGEMENTS

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