Final Technical Report: Mu2e at the City University of New York DOE Award: DE-SC0009817

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Closeout Report
Report Period: 1 June 2013 – 31 March 2017

1 Contributions to Mu2e

This DOE grant award for was for the period June 1, 2013 to March 31, 2016.[1] Popp was awarded an internship in the Visiting Faculty Program at FNAL in summer of 2015; consequently the unused portion of summer salary funds allowed us to apply for a no-cost extension with our remaining funds until March 31, 2017. That support furnished us with the means to carry out numerous successful projects for Mu2e for nearly four years. Up to now, the driving force to our work has been dictated primarily by the Mu2e Project cost and schedule needs. Our work has been under the purview of three of the Working Groups to which we belong: Target Station, Electron Tracker, and Stopping Target Monitor. We have carried out a mix of bench-top testing tasks locally, more elaborate work at Fermilab every summer, and extensive software development and simulation studies.

2 Experimental HEP at The City University of New York

Our participation in Mu2e was centered at York College,[1] one of the eleven Senior Colleges of the City University of New York system (CUNY).[2] CUNY is the largest city university system in the world, and the third largest public university system in the United States. It consists of the Senior Colleges, seven Community Colleges, the Graduate Center (which houses the Physics Doctoral Program),[3] and a number of other specialized divisions. More than half a million students (both degree and non-degree) are currently served by the CUNY system. The York Campus itself is located in Jamaica, Queens, and draws its mainly undergraduate population from Jamaica and surrounding neighborhoods; over seven thousand students attend York. We are a designated Title III Minority Serving Institution.

We are both professors in the Physics Discipline of the Department of Earth and Physical Sciences and members of the Graduate Center Faculty. Faculty in the CUNY system are on a seven year tenure/promotion schedule: Popp is in his ninth year and is a tenured Associate Professor; Lynch is in his seventh year, and earned tenure and promotion to Associate Professor, effective September 1, 2017. Despite being the smallest of the science departments at York, we account for two-thirds of all the General Education Science credits earned on this campus, while the physics discipline courses enroll well over 150 science students per semester, and over 200 general education students. We have a small but thriving physics program, on par with national averages in size and educational outcomes. The University expects us to devote at least one third of our time during the academic year to research pursuits; together with summer and winter months (during which we do not teach), this equates to 0.5 FTE of effort per faculty member. We hire undergraduates in engineering, physics, and/or computer science to provide additional effort to our projects. We engaged six undergraduates and seventeen high school students in meaningful projects in our research program over the last six years at no cost to the DOE; these efforts have been funded by the College administration through institutional grant funds from the Department of Education.

We aggressively and successfully pursued supplementary funding for our work outside of the Department of Energy, particularly for capital equipment. The State of New York - through the Graduate Research and Technology Initiative (GRTI) program - provides funds

[1] "Mu2e at the City University of New York", June 1, 2013 through March 31, 2016, Kevin Lynch and James Popp, $291,000, Department of Energy Grant DE-FG02-13ER41931

to faculty for capital research equipment. Between us, we have been awarded $230,327 during the 2008-2016 calendar years; $40,000 of this total in the current year. We applied this funding primarily to build and instrument our lab spaces for general purpose HEP tasks and to expand our vacuum science capabilities for use in Mu2e Tracker projects. The City University - in collaboration with the faculty union, the Professional Staff Congress (PSC) - provides small, competitive grants to faculty through the PSC-CUNY grant program. We have been awarded $33,720 during the past few years, which has supported travel to Fermilab for Mu2e business and the purchase of test and measurement equipment for our Mu2e research. The Mu2e Project Office awarded us a $12,900 contract to support development and construction of the Mu2e Electron Tracker; the College has purchased an additional $4,500 worth of equipment in 2016 to match project money to assist us in preparing our labs for Tracker straw tube termination production. We recently secured $147,707 from the Department of Defense to purchase a high purity germanium detector system which we will use in Mu2e Stopping Target Monitor studies, and perhaps in the experiment itself. Finally, we note that Popp spent two years (from September 1, 2009 to August 31, 2011) at the Laboratory as a Visiting Scientist, funded by the Mu2e Project Office, as well as the summer of 2015, funded by the DOE Office of Workforce Development for Teachers and Scientists (WDTS) through the Visiting Faculty Program.

During the performance period of this grant, we were coauthors on more than sixty internal Mu2e memos and talks,[4–70], an IEEE conference proceeding,[71], one conference poster presentation,[72], and the technical design reports of both experiments.[73, 74] We were active in presenting the progress of our experiments to the wider physics community over the period of the grant: Popp represented the Mu2e Collaboration with one seminar [75] and one conference presentation,[76] while Lynch represented Mu2e with one seminar [77], two conference presentations,[78, 79] and Muon $g-2$ with one conference presentation.[80]

3 Target Station

The Target Station working group is responsible for the design and development of the pion production target and related support equipment, including the PS Heat and Radiation Shield (HRS), the Protection Collimator (PC), the Remote Handling System for the Target, and the Proton Beam Absorber. The M4 proton delivery line design is also linked strongly to Target Station design choices.

The target baseline design is a radiatively-cooled tungsten cylinder 16 cm long with a 6.3 mm diameter, supported from the inside of the HRS by a "bicycle wheel" configuration of rings and spokes. The 8 GeV, 8.3 kW proton beam deposits an average power of 700 W to the target, raising its surface temperature to at least 1700 C; under these conditions tungsten oxidation in the 10^{-5} torr vacuum is the primary limitation on target lifetime. The proton beam profile at the target is nominally a gaussian with $\sigma = 1.0$ mm, with significant non-gaussian tails. The M4 beam line delivers the beam to the PS off-axis, and it must be threaded through a complicated magnetic and mechanical environment to strike the target end-on. At various points along its nominal trajectory, the beam passes close by various delicate components, including the superconducting coils of the PS and TS, and care must be taken to understand potential accident conditions and protect those components.

Popp has significant prior experience from designing the MECO production target, and our group joined the target station effort to bring our significant simulation experience to bear

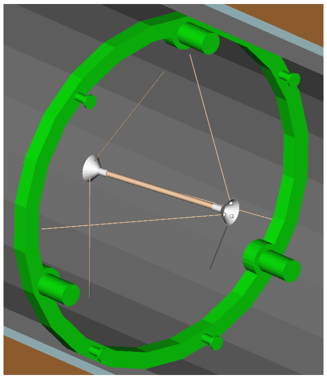 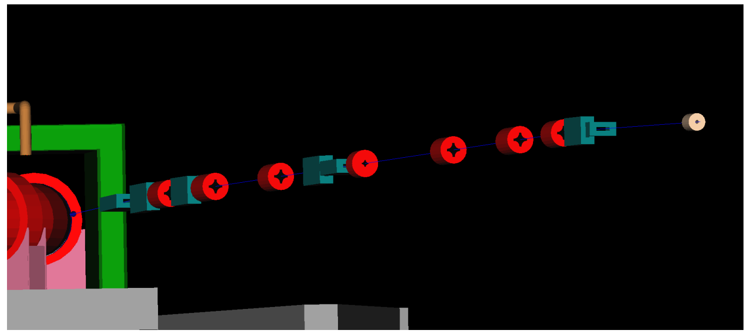

Figure 1: The left hand image shows our detailed G4Beamline model of the Mu2e pion production target. The right hand figure is a close up of the M4 final focus section of the proton beamline, showing details of the magnet apertures.

when the Accelerator Division was unable to provide the necessary manpower. The Mu2e Target Station working group uses the G4Beamline,[81] simulation package for development studies. G4Beamline is a rapid application development package providing a simplified interface to the underlying Geant4 simulation toolkit. We gained extensive experience with G4Beamline and the Mu2e model in particular over the last four years, and have made and continue to make significant contributions to target station development.

In collaboration with physicists in the FNAL Accelerator Division, we advanced the G4Beamline model to accurately reflect the current target and support design in the PS; see Figure 1. We also rebuilt the entire G4Beamline simulation of the final focus region of the M4 proton beamline in the Mu2e model. Our efforts resulted in a very advanced proton beam simulation beginning 67 m upstream from the PS at the final shield wall. We incorporated all the dipole and quadrupole magnets with realistic geometries (apertures, fields, etc.) as well as most instrumentation apertures in the Mu2e integration model. We also worked with the accelerator physicists developing the slow extraction process to incorporate realistic proton beam profiles in our studies.

We focused our most recent efforts on two issues to support transition to operations activities: target scanning and beam intensity reduction for calibration. The requirements for beam steering at the target are ± 1.0 cm in the vertical and horizontal; this level of control is not difficult to demonstrate. However, the quarter degree requirement on the beam angular motion is much more challenging. We demonstrated how to control and measure beam-target alignment so that the experiment can carry out routine target scans with confidence. We also showed the utility of placing a wire chamber in the target hall during these startup scans to determine the precise alignment of the beam and target, and showed that a standard - rather than expensive custom - beam monitor chamber will suffice for this task. We also demonstrated that the primary beam intensity reductions required by various detector calibration schemes are feasible within the steering, aperture, and Delivery Ring extraction constraints available in the design. Finally, we showed that the protection collimator as designed should prevent any mis-steered primary beam from damaging any of the superconducting coils in the TS or PS.

The target station has reached the final design phase, and prototyping activities have begun. We expect to continue simulation tasks with G4Beamline to answer questions that arise during this prototyping phase, particularly how detailed design choices affect muon yields and backgrounds. We continue to address a number of issues:

- The lifetime of the target is dominated by oxidative surface erosion driven by poor vacuum and high surface temperatures. Further reductions in vacuum level are cost prohibitive, so the target station group is investigating methods of reducing the surface temperature. One can increase the emissivity - and hence reduce the temperature at constant power input - by machining fins onto the surface of the target. We have simulated the effects of various axial fin designs on muon yields, giving design guidance to the engineering team.
- Due to the beam intensity and radiation environment surrounding the target, it is not possible to install permanent beam position monitoring equipment, nor is it possible to observe the target within the PS bore in real time. Both the extinction monitor spectrometer and the muon stopping target monitor provide indirect estimates of pion production and may prove useful in providing beam-target alignment during running. We also began studies of the utility and sensitivity of these devices as beam alignment monitors.

We expect to provide additional simulation effort - with a small time commitment - to the target station group as small design changes are proposed in coming years. We have recently begun related simulation work to define the targetry and beam requirements for a next generation follow-on to Mu2e, dubbed Mu2e-II, and represented the Collaboration at a High Power Targetry Roadmap workshop at Fermilab.

4 Tracker

Our group at York actively participated in the development of this one-of-a-kind, ultra-light tracking detector that consists of approximately 22,000 aluminized Mylar wound straw tube drift chambers. This detector really pushes the limits of thin materials detector technology with wound straw wall thickness 15 μm. The straws have a 5 mm diameter and range in length from 430 mm to 1200 mm. The tubes are filled with an 80:20 mixture of Ar and CO_2 at 1 atm. A wire-straw potential difference of 1.5 kV results in a maximum drift time of about 50 ns. The front-end electronics uses TDCs to read out both ends of the 25 μm diameter gold-plated tungsten sense wire running down the middle of each tube. Pulse timing provides position resolution along the wire to 30 mm. Position resolution perpendicular to the wires is much better, with 200 μm resolution. ADC readout for each wire is employed to do particle ID.

4.1 Straw Tube Panel Vacuum Testing

The Mu2e tracker is a high-rate detector designed to operate in vacuum. The DS vacuum volume must operate below 10^{-4} Torr. York College continues to lead the vacuum testing efforts. Popp designed and commissioned a large, high-vacuum chamber at Fermilab for testing tracker panels. This vacuum system consists of a cylindrical stainless steel chamber 2000 mm long and 650 mm in diameter. Each end has a removable cover the diameter of the chamber. There are 6 in diameter ISO 160 ports on each cover for mounting a 250 ℓ/s (N_2) turbomolecular pump, feedthroughs for power, high and low voltage, signal, and circulating coolant for the front-end electronics, and the gas mixture for the straws. The large capacity backing pump is a scroll type, ensuring minimal chamber contamination. Smaller ports are

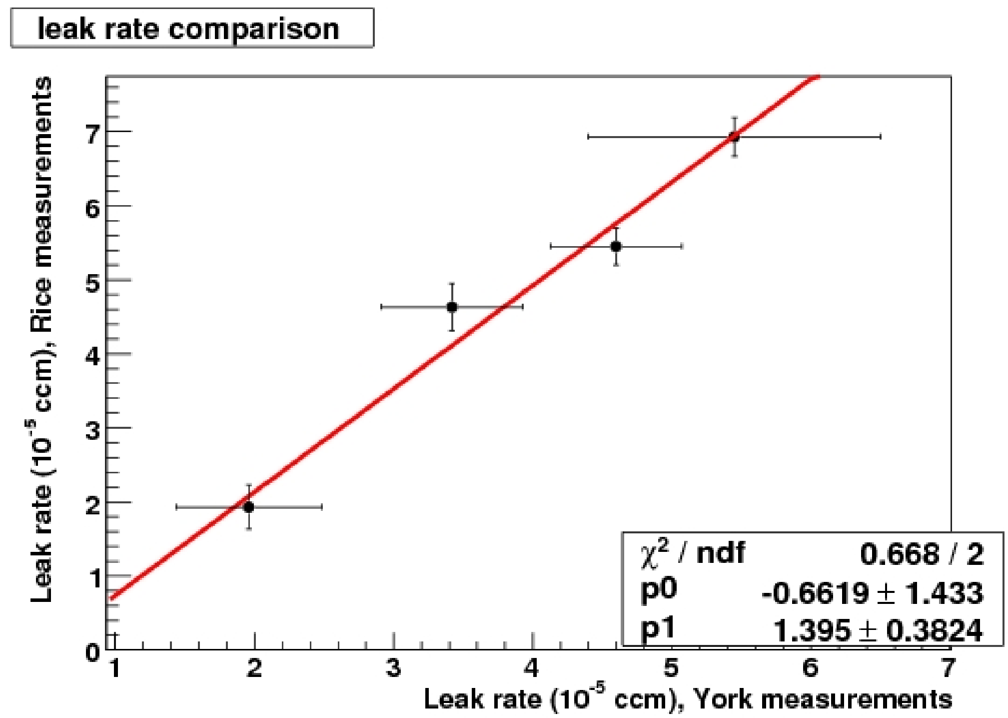

Figure 2: Comparison of York vacuum leak tests of Mu2e tracker straws with Rice CO_2 leak measurements, showing good correlationg between the two methods.

also available for mounting pressure sensors, etc. The base pressure is designed to be in the range $10^{-4} - 10^{-5}$ Torr. The pumpdown time to base pressure with the steady gas load from 100 straws - typical of a single tracker panel - is designed to be less than 30 min. This test chamber has been in active operation for over two years to develop tracker panel test protocols using the latest prototypes.

4.2 Straw Leak Tests in Vacuum

A reliable and fast straw leak test is essential for quality control during tracker construction. Our group developed a reliable vacuum test to measure the straw leak rate directly. Ideally, the leak rate of each straw should be tested in vacuum with the design gas mixture. The characteristic leak rate of the 130 cm long metalized straws to be manufactured for Mu2e is about $1.0 \times 10^{-4}\,\mathrm{cm}^3/\mathrm{min}$ at STP. This low rate poses a serious challenge to designing a cost-effective test that can be carried out in vacuum in as little as 15 minutes. An accelerated test monitoring pure CO_2 leaks has been developed at FNAL to indirectly monitor an upper limit to the total leak rate. Rates extrapolated from this simpler test have been shown to correlate with the York vacuum measurements; see Figure 2.[82]

The production plan is that all straws will be screened using the CO_2 test, while a few percent of these will be randomly selected and tested using the York vacuum test system. The York test protocol can currently be carried out in about 8 hours per straw. Protocol accuracy and precision will be monitored using standardized calibrated leaks. We constructed two chambers which are fully operational and are preparing to build two more to carry out this QC task, ensuring that vacuum testing can maintain pace with the planned straw processing rate.

4.3 Hardware Database Development

The detector construction and testing process will produce a significant amount of quality control data: straw vacuum leak rates, actual lengths after cutting, tension at installation, etc. Storage, tracking, and retrieval of all this data will be useful for quality control and assurance, as well as future calibration, failure tracing, and aging studies.

Working with database experts in the Fermilab Scientific Computing Division (SCD), Lynch took the lead role in the production of a quality control database infrastructure, based on the successful experience of the Nova experiment. Lynch serves as the Mu2e Experiment's scientific contact for the database, and has been responsible for defining the data schema for Tracker construction tasks and the development of database software for the vacuum leak testing system. He is also coordinating with and assisting the other detector subprojects during the ongoing development of their construction database workflow.

The system is based on the "Hardware DB" system developed for Nova. The underlying storage is a Postgresql database, maintained and protected by professional database management staff at the Lab. The interface to the database is provided by a pair of web services (one for insert and one for query), again developed and maintained by professional staff. Access is provided both through a web browser interface, as well as programmatically via Python language shims provided by SCD . The Experiment is responsible for developing the data schema, defining the data to be collected and stored and the relations between those data. We also develop the software that collects, validates, inserts, and queries the data; most software will be developed in Python, a modern object oriented language with excellent support for rapid application development, GUIs, and database interaction. We envision a Nova-like production work flow, with barcoded components moving between work stations where various construction and measurement steps are performed and recorded. We will track as many production steps as reasonably possible, tagging them with work station and worker data, environmental, and tolerance data.

4.4 Stopping Target Monitor

The figure of merit for Mu2e is the ratio of conversion events to capture events, $R_{\mu e}$. This is simply the ratio of two counting experiments: the numerator is the number of conversion candidates observed by the electron tracker and calorimeter, while the denominator is the number of nuclear capture events. For aluminum, the ratio of nuclear capture to DIO events is well known, such that a direct count of the number of stopped muons is equivalent to counting the captures. Unfortunately, the flux of muons will be too high for a direct count; instead, we will count a small, representative fraction of the hard photons emitted in the atomic capture cascade process, and in the decay of the excited nuclei. We will count three promising gamma ray peaks:

1. a prompt $2P \to 1S$ atomic transition occurs at 347 keV, within picoseconds of the muon stop,
2. a semi-prompt 1809 keV gamma emitted during nuclear capture with a lifetime of 864 ns, and
3. a delayed gamma at 844 keV resulting from the decay of the resulting excited Mg nucleus with a 13.6 min half life.

The intensity per muon stop of these channels are well known; together with the measured solid angle and efficiency of the detector used to observe them, we can determine the absolute number of muon stops with good accuracy. To meet the single event sensitivity goal of Mu2e, we must measure these stops to better than 10% once all systematics are accounted for; this is proving to be a significant challenge that will require ongoing effort.

The preliminary design for the Mu2e Stopping Target Monitor (STM) relies on a complementary pair of calorimeters to efficiently cover the wide energy range above: a high purity germanium (or HPGe) system, and a $LaBr_3$ scintillating crystal. The crowning strength of HPGe is the extremely fine energy resolution for gamma ray measurements - much better than 1% in most scenarios. This strength, however, comes at the cost of event rate capability and stopping power - for higher energy gammas, a relatively small fraction of the photon energy is fully contained within the crystal, leading to small relative efficiency. Event rates are generally limited to about 100 kHz by deadtime and energy linearity issues. Scintillating crystal calorimeters can largely compensate for these problems, particularly for higher energy gammas, as they can be read out at rates measured in megahertz. The price to be paid is energy resolution; even a large detector can only be expected to measure gamma peaks with a few percent resolution. We choose $LaBr_3$ for this application because it is fast, dense, and bright, which gives it the capability to do fast timing (nanosecond scale resolution) with high precision (around 3% for a 3 in by 3 in cylindrical crystal).

In the last year of the grant period, we rescoped our efforts to respond to the needs for leadership on the STM design and development. We pursued and secured non-DOE external funding for to purchase a high purity germanium detector, and are pursuing additional funds for inorganic crystal calorimeters and high speed data acquisition electronics for this detector system. [62, 68] We have been an integral part of defining the data acquisition requirements [60], the power requirements [61], and the "vertical slice" functionality test requirements [69]. We participated and reported regularly on the status of the STM design to the Mu2e Electrical Integration group. We continue to work on developing the plans for data acquisition, and have also joined the simulation effort to better define the STM alignment, normalization, and calibration requirements and design.

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