Fermilab LDRD Proposal

Project Title: Beam Precision Time Profile Monitor

Principal Investigator: Eric Prebys
Lead Division/Sector/Section: AD/APC
Co-Investigators (w/institutions): Professor David Hedin, Northern Illinois University

Proposed FY and Total Budgets: (summary of budget page (in dollars))

	SWF	SWF OH	M&S	M&S OH	Contingency	Total
FY16	13,707.96	11,705.23	93,463.00	21,991.84	50,000	199,868.03
FY17	9,609.11	8,205.22	0.00	0.00	10,000	27,814.33
FY18						
Total	23,358.80	19,910.45	93,463.00	21,991.84	60,000	218,724.09

SWF: Salary, Wages, Fringe   SWF OH: overhead on SWF
M&S: Material and Supplies M&S OH: overhead on M&S
Contingency (estimate of additional funds that might be required with justification)

Initiative: 2015 Broad Scope

Project Description (150-200 words):

The goal of this project is to measure the fraction of beam that falls outside of the nominal RF bunches, with a sensitivity of at least 10^{-5}, a regime where confidence in computer simulations is limited. Such longitudinal tails have significant implications for beam and acceleration efficiency, and are therefore an important consideration for all experiments where beam loss is a factor. At Fermilab, this will be particularly important as we increase the intensity of the Main Injector in the coming years. In the near term, this measurement is important to the Mu2e Experiment, which has very stringent limits for out-of-time beam. The general problem of such measurements is the large dynamic range required to directly measure the beam intensity. Our proposed technique uses a statistical method, in which a charge telescope is used to monitor beam scattering off of an existing multi-wire or multi-foil installed in the beam line. An accurate time profile will then be built by integrating over many bunches. The sensitivity is expected to be at least two orders of magnitude better than that which can be achieved with traditional techniques, such as resistive wall monitors. This detector will use the Recycler beam scrapers to scatter particles, to evaluate the 2.5 MHz Recycler bunches. The results can be directly compared with simulations, which is in itself of fundamental interest to the accelerator community. These measurements will also provide valuable insight into Recycler operation for future experiments.

Significance (~1-2 pages):

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. 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. Out of time beam is also very important to the Mu2e Experiment at Fermilab. In order to achieve the extinction level required by the experiment, it is necessary there be no beam outside of these 2.5 MHz Recycler bunches at the 10^{-5} level or less. Beam simulations show this should be possible [2], but given the importance, it is very desirable to validate these models with measurements, so that contingency plans can be made if there is a problem. Such precise measurements of longitudinal structure have never been made at Fermilab, and there is little experimental validation of models at this level in general.

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. 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 [3]. 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.

Research Plan (~3-4 pages): Provide a brief overview of your research plan and your specific objectives or aims. For each objective/aim, provide a section with the following:

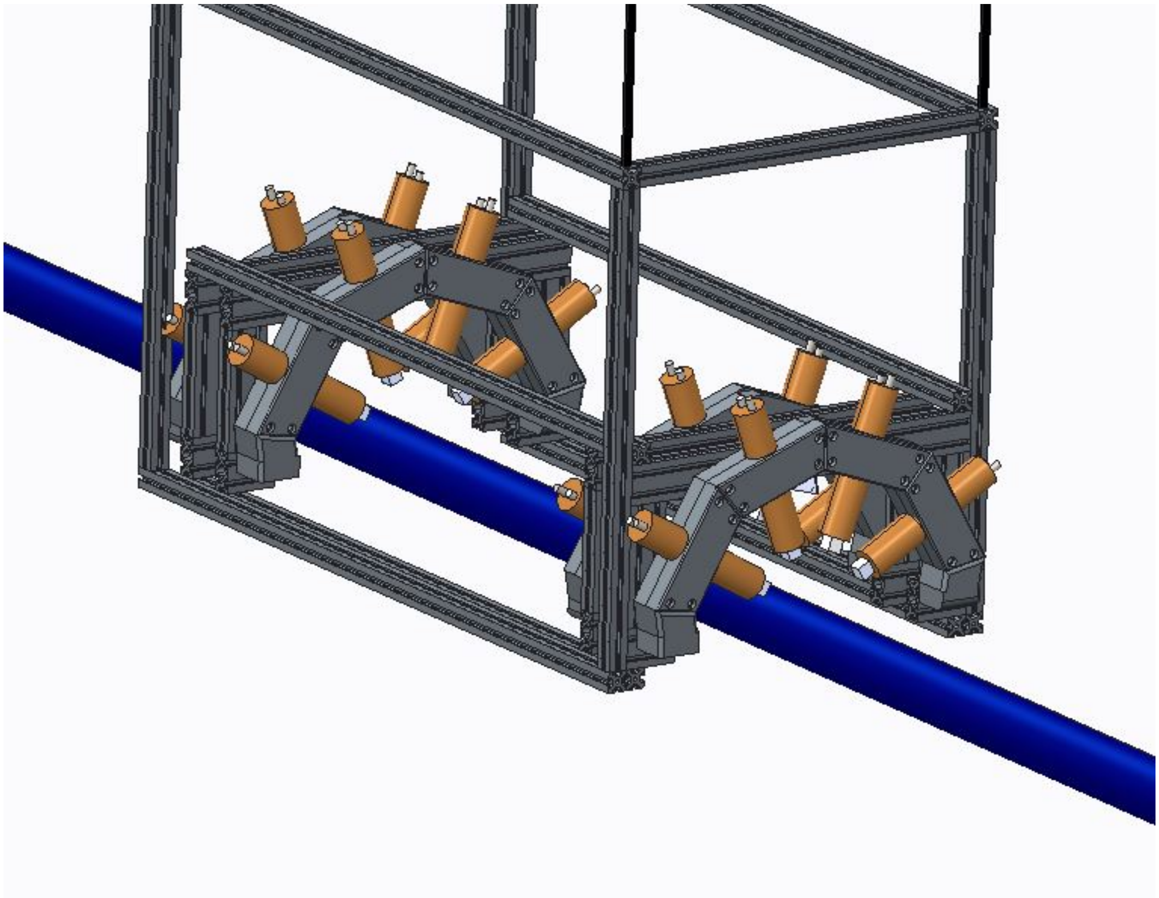

Figure 1: Charge telescope. The exact location and angles will be optimized to give a few tracks per nominal bunch.

a. *State the objective/aim*

The objective of this project is to measure a precise longitudinal profile for 2.5 MHz proton bunches of 1×10^{12} protons each, with a sensitivity of at least 10^{-5} (10^{7} protons) for out-of-time beam.

b. *Describe the scientific hypotheses to be tested or technical concepts to be demonstrated to achieve the objective/aim.*

Simulations of the 2.5 MHz bunch formation in the Recycler indicate that there should be very little coasting beam outside of the nominal bunches[4]. This measurement will test the accuracy of these models by measuring beam between the bunches. Understanding such out-of-time beam will be of value to numerous intensity frontier experiments.

c. *Discuss the methods, materials, facilities, protocols to be employed, and techniques for analyzing data and validating results as appropriate.*

As described above, this technique involves scattering beam into a detector with a limited acceptance. In this case, the scattering will be provided by the scrapers in the Recycler, which are located at location 621[5]. The detector is illustrated in Figure 1. Particle detection will be accomplished with 4 arms, consisting of 4 quartz radiators

The radiators are each attached to UV sensitive photomultiplier tubes, such as the Hamamatsu R7056 (sensitive from 185 to 650 nm). The entire assembly is focused on the scattering scraper. The quartz radiators rely on Cerenkov radiation. They have been chosen over scintillators for three reasons:

- They have a very fast response.
- They have no intrinsic after-pulse/afterglow.
- They are blind to neutrons and other soft particles.

To expand on the last point, they are only sensitive to charged particles with $\beta>2/3$, therefore they operate in a regime where we trust the simulation of the production of particles from the scrapers.

The structure will be constructed out of 80/20 elements[6], which is a standard technique at Fermilab. The orientation is quite flexible and the device can be oriented to accommodate other hardware in the tunnel. Modeling will be done to determine the optimum location for the telescopes. The goal is to have an average rate of approximately 1 track/arm/nominal bunch, to avoid any pile-up problems. An engineering student at NIU will do most of the design, but we have budgeted some time for a Fermilab Mechanical Engineer for miscellaneous final mounting fixtures that may be needed.

Analog signals from the 16 PMTs will be connected to waveform digitizers, which will allow the time structure of the Cerenkov light produced during the beam pulse to be analyzed in detail. Since the quartz radiators are arranged in a projective geometry, a simple coincidence can be used to find tracks. Data acquisition will be synchronized to the 2.5 MHz RF clock which is used to generate the bunches. A μTCA crate will provide the framework for the data acquisition. This readout is similar to a system that NIU built for the proton therapy center at Central DuPage Hospital.

The project plans is to use a commercially available high voltage system, and the current budget estimate is based on a quote from Wiener, Plein, & Baus, corp[7].

Installation will take place during the summer 2016 shutdown. Once beam starts up again, we will request study periods on the Recycler. Studies will use Booster beam, which will have been bunched into 4 bunches by the 2.5 MHz RF system. Scraper position will be optimized to produce the desired 1 track/arm/bunch average rate. We would like to measure out-of-time beam at the 10^{-5} level. Assuming we need 10 tracks to establish this level, we want a minimum of bunch crossings (n_{bunch}) that satisfies

$$(n_{bunch}) \times (1 \text{ track/arm/bunch}) \times (4 \text{ arms}) \times (10^{-5}) = 10$$
$$\rightarrow \quad n_{bunch} = 250{,}000$$

Since there will be 4 bunches per 11 μsec period of the Recycler, it will take about 0.7 seconds to gather this minimum amount of data. Running for longer will allow a more detailed map of out-of-time beam to be made. In any event, the actual data taking time required will be negligible, and study time will be dominated by set up time.

d. *Describe the expected results and impact (e.g., fundamental breakthroughs, enabling technologies)*

At the end of this study, we will have experimental data on the relationship between out-of-time beam on bunch intensity and RF voltage, which will be used to validate computer simulations. These results will have relevance to future high intensity experiments, and will be relevant to the Mu2e Experiment in the near term. If the out-of-time beam proves to be much worse than predictions, the Mu2e extinction strategy may have to be re-evaluated.

e. *Provide a deliverable(s) for year one (within the first year of funding), year two (if seeking a multi-year project), and at the completion of the project.*

The deliverables for the first year will be the device, installed in the Recycler tunnel, the HV system, data acquisition system and any software required to take data.

The deliverable for the second year will be the data taken by the device, and the analysis of that data. This will include the dependence of the fraction of out-of-time beam on bunch intensity and RF voltage, and will provide valuable comparison between simulations and reality.

In addition to the experimental validation of the beam simulation models, the deliverable at the end of the project will be the device itself, which can be moved to other locations for other uses.

Future Funding (~1/2 page):

a. *Describe how your results will be disseminated; include likely journals in which your work would be published and conferences, workshops, and planning activities at which the work would be presented.*

The results will be made available to the people working on experiments at the lab, it will also be presented at PAC and/or iPAC meeting, as well as a variety of undergraduate research conferences and workshops, such as the National Conference on Undergraduate Research (NCUR). Results will also be published in NIM and/or PR-STAB.

b. *List the probable future funding sources (sponsors), including DOE programs, other agencies, state agencies, or private sector investment.*

We do not anticipate the need for any future funding for this project. If another group wants to use the device, they will need to support the small cost of moving and installing it in a new location.

c. *For each probable funding source:*

- *Explain how the sponsor would benefit from the pursuit of this work.*
- *Discuss probable contacts with sponsors and plans for responding to current and planned proposal calls.*
- *Estimate the likelihood that the sponsor would provide future funding including anticipated range of such funding.*

N/A

References

[1] Mu2e Collaboration (R.J Abrams, *et al*), "Mu2e Technical Design Report", Mu2e-DOC-4299 (http://mu2e-docdb.fnal.gov), 2014, p. 4-168

[2] *ibid*., p. 4-175

[3] K. Ehret, et al., "Observation of coasting beam at the HERA Proton-Ring", arXiv:hep-ex/0002002v1 (2002)

[4] I. Kourbanis, "Bunch Formation for g-2 Experiment", gm2-DOC-335 (http://gm2-docdb.fnal.gov/), 2012

[5] C. Gattuso, FNAL, *private communication*.

[6] "80/20, Inc. The Industrial Erector Set", http://www.8020.net/

[7] "Wiener, Plein& Baus Elektronik", http://www.wiener-d.com/

Qualifications

Full CVs for both PIs are attached. Selected relevant qualifications follow:

Dr. Eric Prebys, Fermilab

Dr. Prebys is a Scientist II at Fermilab with 30 years of experience in a wide variety of detector technologies and associated data acquisition systems, including direct experience with the electronics and low level data acquisition of the sort that will be used on this project. He also has extensive management experience, including 5 years as head of the Fermilab Proton Source, and 5 years as head of the US LHC Accelerator Research Program (LARP).

He is familiar with Fermilab accelerator operations, as well as the accelerator controls system (ACNET), which will be valuable in scheduling and performing the required beam studies, once the device is installed.

Professor David Hedin, Northern Illinois University

Professor Hedin has been on the faculty of NIU University since 1987. He is currently a Distinguished Research Professor and Board of Trustees Professor. He and the NIU group played an important role in the design, construction, and operation of the D0 experiment at Fermilab, particularly with the scintillator counters used in the central muon system, which uses photomultiplier tubes similar to those in this detector.

The group also built a proton tomography device, which is now undergoing tests at Central DuPage Hospital. Our data acquisition system is patterned after this device.

In addition to physics contributions, the NIU group can provide mechanical engineering, machine shop facilities and machinist time, and student labor to the project.

Resource Availability and Recent LDRD Funding

(not included in 6 page limit):

> ***a.*** *Discuss scientific or technical obligations of the investigators that may limit the available time for working on the LDRD project (e.g., other funded research, participation in scientific committees, etc.); use units of FTE's to estimate the time*

Estimated time commitments of PIs follow:

Eric Prebys
0.30 FTE: Mu2e Experiment

0.40 FTE: IOTA Project
0.10 FTE: LARP-related R&D
0.05 FTE: Lee Teng Undergraduate Internship (program director)
0.10 FTE: Other Committee Assignments and misc.
0.05 FTE: This project

<u>David Hedin:</u>
0.47 FTE: Faculty (teaching, administrative)
0.03 FTE: D0 Collaboration
0.30 FTE: Mu2e Neutron Task Force and MBS design
    0.10 FTE: Other Mu2e
    0.10 FTE: This project

b. *List other LDRD commitments of the investigators; include both current (funded projects) and pending (new proposal) commitments; use units of FTE's to estimate the time*

None

c. *Summarize accomplishments of funded LDRD projects for the last five years (include project title, investigators, and year of project)*

No previous LDRDs for either PI

Budget Table (not included in 6 page limit, separate document): *The last page of the proposal consists of a completed budget table. In the budget table, include a cost breakdown for each objective/ aim discussed in the Research Plan. There is no specific budget limitation, but keep in mind that the LDRD funding has limited resources. If subcontracting work, it should be clear in the proposal what work is being subcontracted and justified why that work is not able to performed within Fermilab.*

Attached.