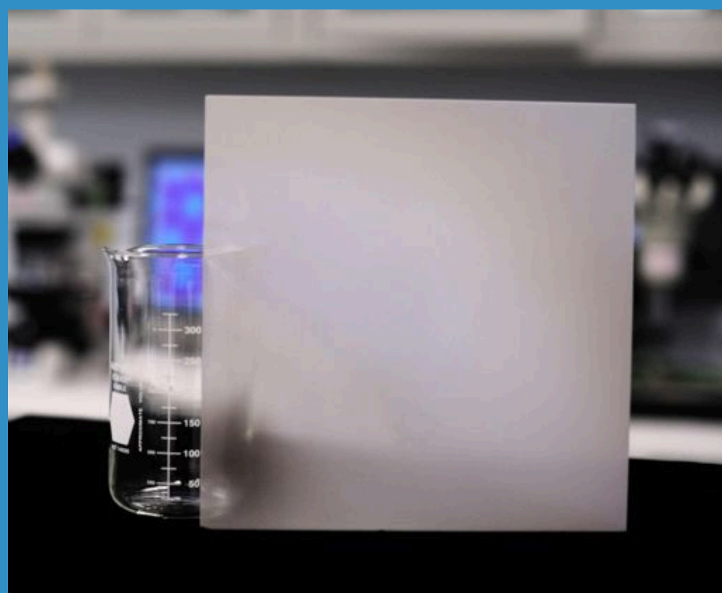
R&D Proposal for 10 Picosecond TOF PID at an EIC



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Introduction

This proposal intends to explore the possibility of a Time-of-Flight detector for particle identification at an EIC, using very high performance (10 picosecond resolution), 8”x8” MCP-PMT tiles that have been developed by the LAPPD collaboration. The LAPPD project, led by the University of Chicago and Argonne National Lab, have successfully demonstrated an alternative production method for high performing MCP-PMT’s based on atomic layer deposition on glass capillary plates. The project is currently in an SBIR Phase-II stage, which is funding the pilot line for production at Incom USA, Inc. With this development, there is the genuine hope that eventually mass manufacturing techniques will reduce the cost by an order of magnitude over comparable MCP-PMTs available today, and allow for the large area coverage that is needed at an eIC detector.

MCP-PMT’s have been investigated in the past decade for their extremely good timing performance, and their large area coverage, but their extremely high cost has prevented wide adoption. For example, a Photonis XP85012 MCP-PMT, which has been demonstrated to achieve better than 10 ps resolution, costs more than $12K per 6x6 cm^2 tube.

The LAPPD project was funded to explore an alternative, more cost effective method for producing MCP-PMTs using glass capillary plates functionalized by atomic layer deposition (ALD). Normally, the technique for producing MCPs consists of chemically etching a fused fiber optic that is produced using expensive specialized core and clad glass. The core glass gets etched away from the plate of clad glass producing the pores. The remaining porous plate is then hydrogen fired to produce a thin layer of semiconducting reduced lead oxide on the surface of the pores.

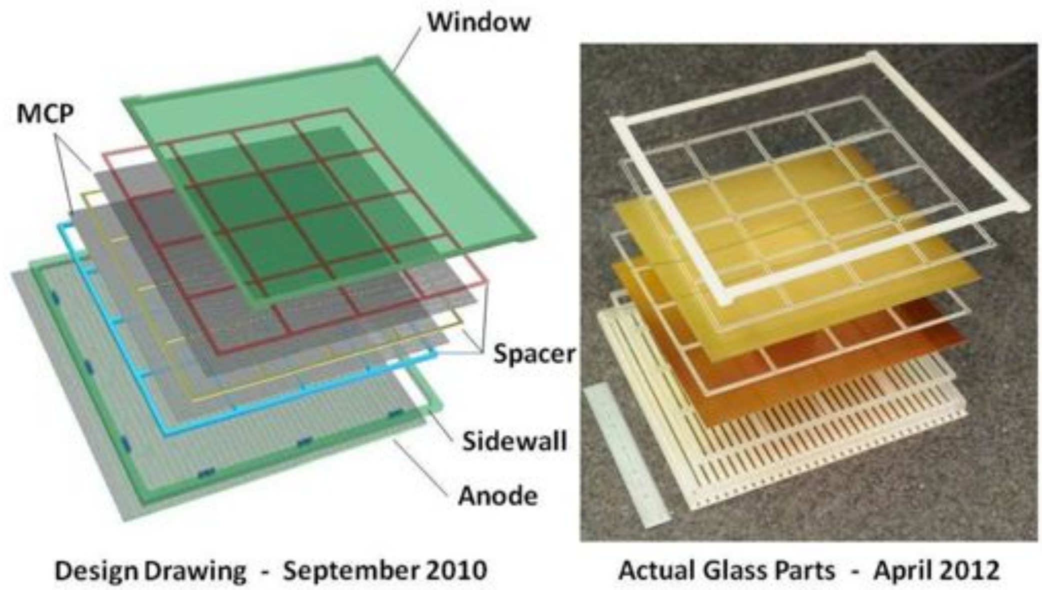

Figure 1: Layers of the LAPPD MCP-PMT, showing the window, the two 10-25 um hole MCPs, and the bottom anode.

The LAPPD collaboration has successfully concluded their 3-year R&D program on these newer, hopefully cheaper manufacturing techniques. In their SBIR Phase-II collaboration with Incom, they have been working on the commercial processes for fabricating the MCPs. In this new manufacturing method, they use a hollow draw process, where multiple hollow glass claddings are drawn and then combined to produce the glass capillary plates, which is shown on the front cover of this proposal. These plates form the basis for the MCP. They are electrode coated, and then undergo atomic layer deposition to tune the resistivity and the secondary emissive function. The plates are finally sealed with the HV resistor chain, the photocathode window, and an anode bottom plate. The layers of these MCP-PMT's are shown in Fig. 1.

Currently there is an "Early Adopters" program to acquire a few first production tiles for testing. These tiles will be available starting in January 2015. While it is too early to determine the price of one 8"x8" MCP-PMT tile, the expectation is that these tiles should be much cheaper per unit area than the current MCP-PMTs, by a factor of at least 3-5. The cost will drop even further with wide adoption of these MCP-PMTs, which could be possible since there is broad interest from the high energy/nuclear physics community, and from medical imaging (TOF-PET), homeland security, defense, and hydrogen storage applications.

Even with the more modest factor of 3-5 in savings, one can contemplate full 4π coverage in a detector. We show two possible detector implementations of full coverage TOF: in the ePHENIX concept, and in the dedicated EIC detector concept. A MCP-PMT based TOF, as one can see, can be used in almost any implementation of an EIC detector.

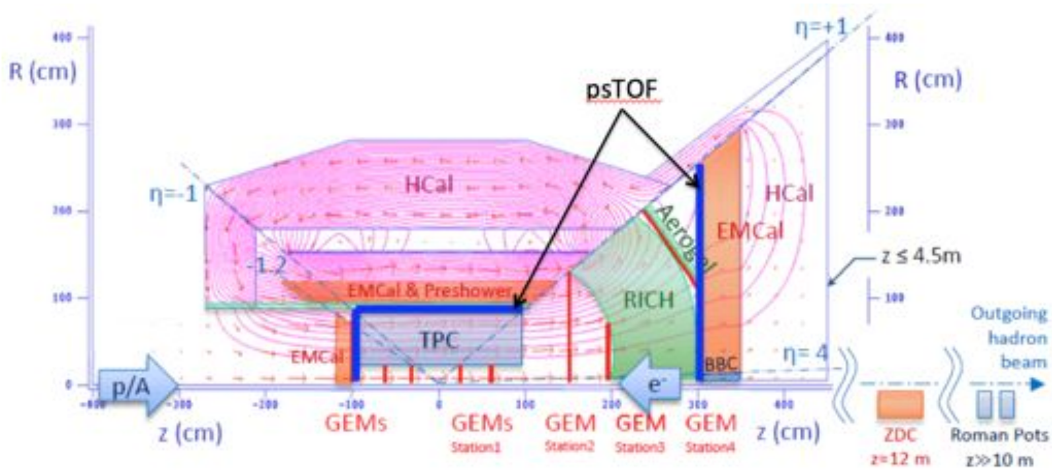

Figure 2: Example of location for TOF walls in one implementation of an EIC detector.

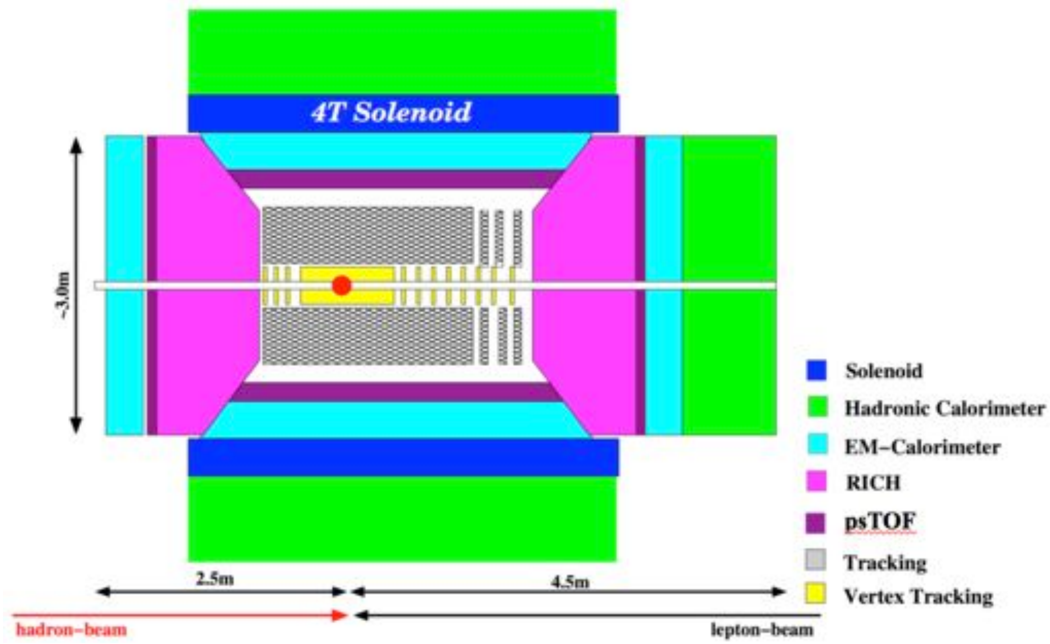

Figure 3: Locations of TOF walls for a dedicated EIC detector design.

Time-of-Flight PID Using MCP-PMTs at an EIC

To build a TOF device out of an MCP-PMT, one places a fused silica or other solid Cerenkov radiator optically coupled to the MCP-PMT. Depending on the quantum efficiency (QE) of the photocathode, and the transmittance of the Cerenkov radiator and PMT window, one can reasonably expect to get about 50 photoelectrons produced. A schematic picture of the design is shown in figure 4. Since the Cerenkov photons are produced promptly, they should arrive at the photocathode within less than a picosecond of each other. This is true for particles at normal incidence, but becomes less true for particles coming in at an angle. One key obstacle to overcome will be determining how to ensure a projective geometry for the MCP-PMT tiles so that particles all arrive at near normal incidence.

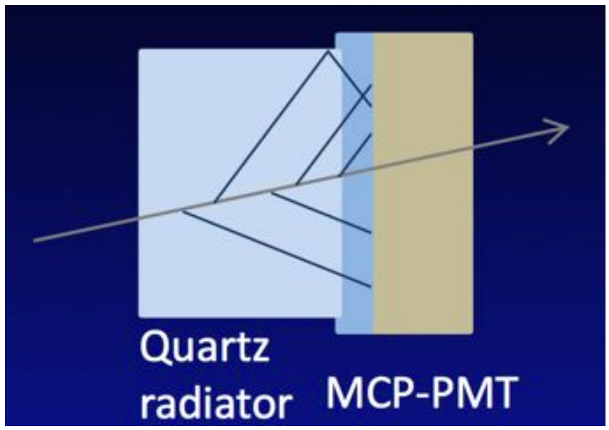

Figure 4: Schematic picture of a direct TOF detector using MCP-PMTs. The quartz (or fused silica) radiator provides a prompt light response onto the photocathode of the MCP-PMT.

A picture of the signal development is show in Fig. 4. The behavior is similar to ordinary PMTs, except that the gain amplification occurs along the inner edges of tiny pores of 10-25 um diameter. The very good timing performance is possible due to the constrained path inside the small diameter pores that the secondary electrons must take, as well as the short distance for the amplification stage. Transit-time-spreads (TTS) of less than 50 ps have been measured for the Photonis and Hamamatsu MCP-PMTs. The gains for the MCP-PMTs are also similar to regular dynode-based PMTs, on the level of 10^6 or 10^7.

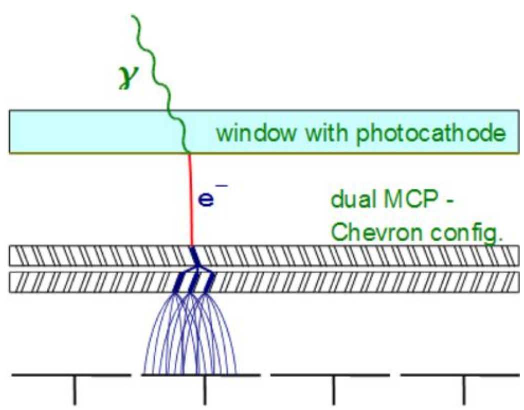

Figure 5: Schematic drawing of the signal development in a MCP-PMT.

The studies needed to optimize the design are being proposed as part of our collaboration's goals. Fortunately, this proposal comes at an early enough stage in the LAPPD production that we have can likely influence the production process to ensure that the Incom produced LAPPD tiles will be suitable for our use. As an example, the QE of the photocathodes which have been used by LAPPD, KNaSb and KCsSB, have cutoffs in the 300 nm range and are not optimal for Cerenkov detection. These aspects will have to be checked carefully for our purpose, and part of the goals of this proposal is to investigate all of these aspects.

For time-of-flight measurements, one crucial aspect is the measurement of a start-time. While this requires further study, we believe there are two possible solutions. One, since the electron beam is expected to have a longitudinal RMS of 2 mm or better. Since 2mm is approximately 6 ps, one could simply derive the start time from the vertex position of the collision point and still attain an overall resolution of 10 ps for the total TOF resolution. This solution requires a vertexing resolution of O(1) mm. The second option is only possible with full TOF coverage. In that case, one can use the time-of-flight of the electron, along with a measurement of the track length, to derive the start time.

Time-of-Flight Performance for PID

Using time-of-flight, when coupled with a tracking momentum measurement, is a well established technique for particle identification. One way to determine the efficacy of particle identification using TOF is to determine the time difference from two particle types, both with the same momentum p but different masses. Over a given flight path of distance L, the time difference between the two particles is

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

$$\Delta t \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2),$$

where the last approximation is for relativistic particles, E ≈ pc >> $m_i c^2$. The momentum reach for PID at a level of 3 sigma is shown in Fig. 6. In the figure one can see the performance of the three distinct regions: the hadron endcap, the central barrel, and the electron endcap.

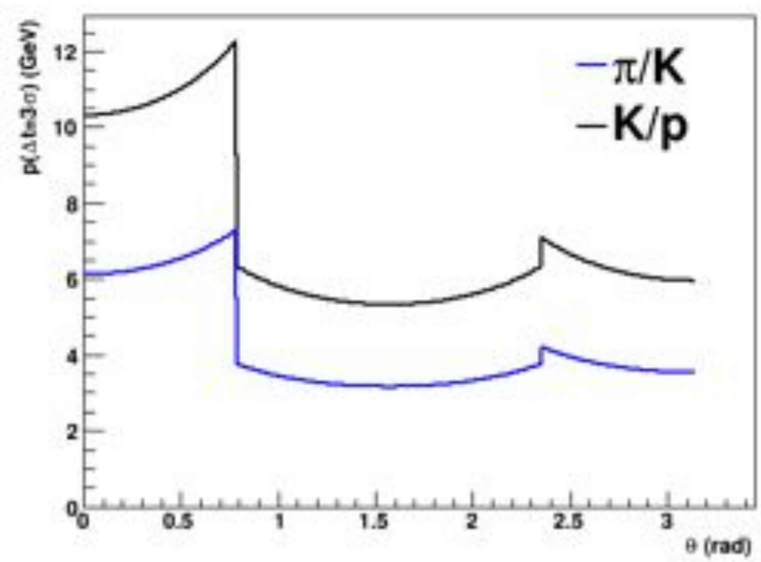

Figure 6: Momentum for 3 sigma separation for pi/K and K/p, assuming TOF wall distances as in the ePHENIX configuration.

Initial studies of the PID requirements for an EIC have been shown in previous proposals to the EIC R&D program. We do not reproduce those studies here, but note that the PID performance will be more than adequate for the vast majority of the rapidity range. Part of the goals of this proposal is to study and understand how the various proposed detector components of an EIC detector could work together to complement each other. For instance, in the forward region one would actually like to extend the range of PID coverage to even higher momentum than our proposed TOF will be able to measure. We believe a TOF will make a great complementary device with a RICH detector; with the RICH tuned to measure at higher momenta. This implies a higher threshold cutoff, but a TOF to cover the lower momenta and a RICH to cover the higher momenta may well be suitable for the EIC.

Studies of how well the TOF PID works for physics observables at the EIC will be done using the existing common framework for simulations. Besides the direct studies for PID of hadrons, we also intend to study whether TOF can be used to improve electron identification, particularly in conjunction with dE/dx in a TPC.

LAPPD MCP-PMT Status

As mentioned previously, the LAPPD collaboration just recently successfully completed a 3-year, $3M dollar R&D program to develop cost-effective MCP-PMTs with comparable performance to existing MCP-PMTs. Many studies have been done and much is known about the performance of the ANL/Chicago produced MCP-PMTs. We present in this section a brief summary of the current status. However, the modules we will actually use are the commercially made variants by Incom so that these studies will need to be re-done with the commercial version.

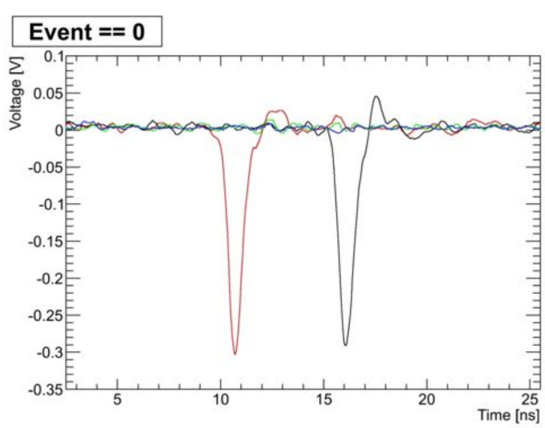

Figure 7: Very first signals from PSEC4 readout of LAPPD MCP-PMT.

The time resolution performance for the LAPPD MCP-PMTs has been reported to be extremely good. Resolutions below 10 ps may be achievable, as seen in Fig.8. In that study, the LAPPD collaboration fired a laser incident on a LAPPD MCP-PMT, and read out the two ends of the strip-line anode. The difference in time between the two was measured to be as low as 6 picoseconds. This includes the additional resolution from the laser spot size of 2 ps, so that the resolution should be even a bit lower than 6. The ultimate resolution will be a function of the amount of signal, which in our case means the number of Cerenkov photoelectrons generated, and the noise in the MCP-PMT and readout electronics, as well as the analog bandwidth of the electronics and the intrinsic resolution of the electronics itself.

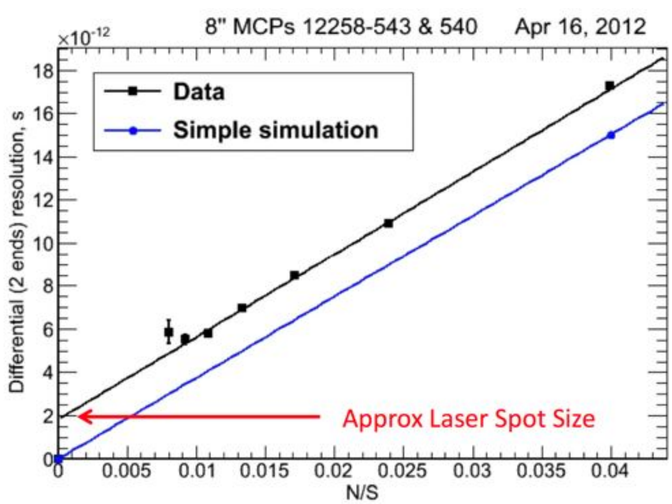

Figure 8: Timing resolution studies using a laser incident on LAPPD MCP-PMTs. N/S is the Noise/Signal ratio.

While the performance has been demonstrated to be very good, those studies were with the ANL/Chicago produced prototype tiles. The new Incom produced tiles will have to be tested when they are available, and optimization studies of their performance will need to be done.

One major deficiency of the present MCP-PMTs has been their relative susceptibility to aging. Losses in QE of ~10-30% have been reported upon accumulation of as little as 1 Coloumb integrated charge per cm^2. The current theory is that the aging occurs from ion backflow onto the photocathode and damaging it. Out-gassing in the Pb-Gl that is typically used to make the MCP may perhaps enhance the ion backflow. In Fig. 9, we show a study of the LAPPD MCP-PMT gain compared to that from typical MCPs. Remarkably, there seems to be very little aging occurring in the LAPPD MCP-PMTs. It is possible that this might be due to the fact

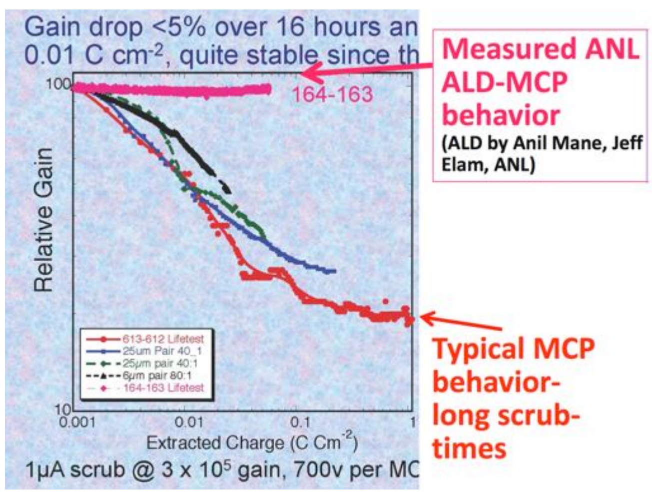

Figure 9: Relative Gain Drop after scrubbing of MCP-PMTs with an intense electron beam. The LAPPD (magenta) is remarkably better.

that the LAPPD MCP-PMTs starts with pure (and clean) glass, which is then modified by ALD. Thus, there might be fewer contaminants to create the ion backflow in the LAPPD MCP-PMTs. Clearly, this needs further study to determine the exact difference in the LAPPD MCP-PMTs to produce such remarkably good behavior.

One aspect that has not yet been studied is the rate capability of the LAPPD MCP-PMT. Studies of the expected hit rate from the EIC will be done to determine what is required. The hit rate will be a strong function of location on the detector, with higher hit rates in the areas in the more forward direction and closer to the beam line. We will then study the rate capability of the Incom LAPPD tiles to determine if they satisfy the requirements.

Another major concern is the viability of the MCP-PMTs in a strong magnetic field, due to the deviation of the electron transport down the pores from the strong Lorentz Forces in the 1-3 Tesla fields envisioned at the EIC detectors. This deviation is strong dependent on the field orientation with respect to the direction of the pores. The Lorentz forces are much smaller if the pores are aligned with the magnetic field than when they are transverse. This potentially poses a problem for placing the MCP-PMTs in the barrel of a cylindrical detector with a solenoidal field, since there the effects of the magnetic field on the MCP-PMT will be largest. While MCP-PMTs have been demonstrated to perform acceptably well for cases where the magnetic is along the axis of the pores, more studies will need to be done for the case when they are transverse, such as would be the case in the barrel region. One possibility is to go to smaller pore sizes, and another is to increase the voltage, thus increasing the electric field drawing the electrons down the pore.

The current state of understanding of the performance of the LAPPD MCP-PMTs is in a high state of flux, as can be expected for such a new detector. Thus, while the list of concerns may seem daunting, some of the concerns we have raised will have been addressed by the LAPPD collaboration over the coming year (2014). Besides that, there is a growing community of scientists with an interest in the LAPPD MCP-PMTs. Some of them are also studying some of these issues, so that we will benefit from their shared research. In return, we believe our group can make decisive contributions through this proposal if funded.

Fast Waveform Digitizing Readout Electronics

The technical challenge of developing a detector capable of 10 picosecond resolution is great, but so has been the challenge of designing cost-effective, low power electronics that is capable of measuring at that extreme resolution. Of course the detector is useless without the electronics to read it out. Currently, much of the research is based on using fast waveform digitizing electronics for fast timing readout. By fast, we usually mean on the level of 10 GSa/s or higher. Usually they incorporate switched capacitor array (SCA) networks and delay line loops to produce fast, correctible timing, and amplitude digitization. It is also possible to use gigahertz TDCs. There are a variety of reasons why the fast waveform digitizer approach is superior. Since one needs to run at high clock rates, the gigahertz TDCs draw a lot of power. In the SCA, the voltages are stored in analog until needed, thus vastly reducing the power consumption. The SCA based ASICs typically draw 10-40 mW per channel. Additionally, with the whole waveform digitized, one can get full information on the pulse, including multiple samples along the rising edge, which vastly improves the total time resolution. Finally, since these chips are custom ASICs, they are fairly cost-effective once produced in bulk. Typical costs are in the range of O($10) per channel.

There are currently many variants of SCA waveform digitizing ASICs that exist today, such as the DRS, PSEC, Wavecatcher, and Target ASICs. However, NONE of the variants can work in a collider environment since they typically only have arrays of around 1024 capacitors. For a system running at 5 GHz, 1024 capacitors constitute only 200 ns, so that in 200 ns all data is lost. Typically at a collider one needs a buffer depth of 4-8 microseconds to satisfy the trigger latency.

There are two ASICs under development which might be suitable for use at an EIC. The DRS5, developed at PSI in Switzerland, builds on the DRS4 ASIC and is scheduled to be available in 2015. The PSEC5, which is the next generation ASIC being developed by U. Chicago and U. Hawaii as part of the LAPPD collaboration, will still have a short SCA buffer, but will incorporate multi-stage transfer of windows of interest to additional analog buffer, and allow for digital buffers of many microseconds. Currently the design specification, shown in Table 1, calls for a 3.3 μs trigger delay buffer. It is not clear yet what the specification should be for the EIC, but as part of our studies we will determine what is needed. The PSEC5 is due to be available in the Summer of 2014.

The PSEC5 ASIC is derived from the PSEC4 ASIC, which is used for many of the studies done by the LAPPD collaboration, and is therefore fairly well tested. For this reason, and since the PSEC5 is available sooner, we have decided to develop our system using the PSEC5 ASIC. We plan to develop a system fully capable of being used in a detector at the EIC, i.e., it should be fully pipelined and near deadtime-less.

Parameter	PSEC4	PSEC5
Channels	6	4
Sampling Rate	4-15 GSa/s	5-15 GSa/s
Primary Samples/channel	256	256
Total Samples/channel	256	32768
Recording Buffer Time at 10 GSa/s	25.6 ns	3.3 μs
Analog Bandwidth	1.5 GHz	1.5 - 2 GHz
RMS Voltage Noise	700 μV	<1 mV
DC RMS Dynamic Range	10.5 bits	10 - 11 bits
Signal Voltage Range	1 V	1 V
ADC on-chip	yes	yes
ADC Clock Speed	1.4 GHz	1.5 - 2 GHz
Readout Protocol	12-bit parallel	serial LVDS: one per channel
Readout Clock Rate	40 MHz	500 MHz
Average Power Consumption	100 mW	300-500 mW
Core Voltage	1.2 V	1.2 V

Table 1: Parameters of the PSEC4 and PSEC5 ASIC. The major changes needed from version 4 are highlighted in red.

One of the major issues with any of these SCA based waveform digitizing ASICs is that there are inherent systematic effects that lower their timing and amplitude measurement performance. These include separate pedestals as well as differences in the timing for each capacitor. This can be seen in Fig.10, where an input sinusoidal signal is measured (red points in the figure). One can see systematic deviations of the time and amplitude in the measurement. Careful study will need to be done to determine the optimal calibration scheme to correct out these systematic effects. In particular, on the new generation of ASICs, where additional buffering is implemented in the ASIC, one at the very least has many more types of buffers to calibrate, and also may run into new issues not foreseen. We hope to help solve these issues through this proposal.

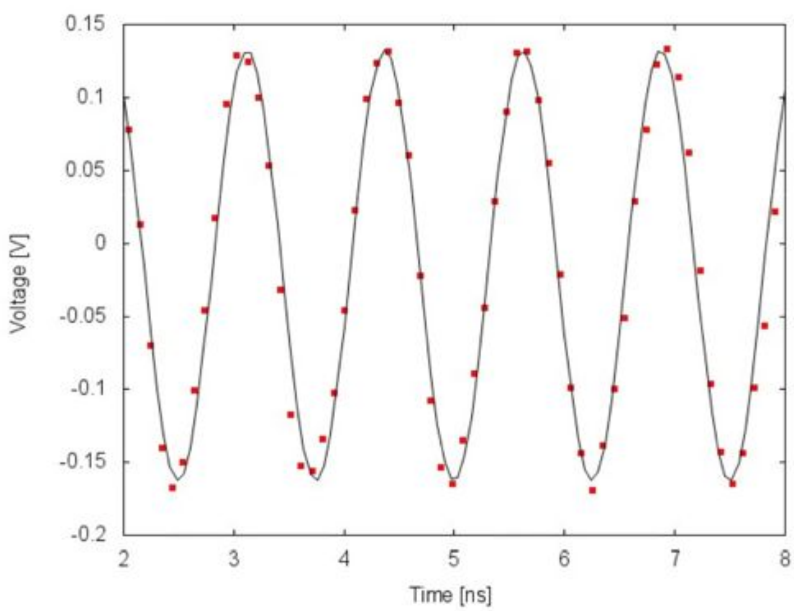

Figure 10: Input pure sinusoid and read out by the PSEC4 chip.

Summary Description of Proposed Studies

In summary, we believe that there is an opportunity to take advantage of emerging developments in large area, very high performance, and cost-effective MPC-PMTs that would be very useful at an EIC. While we have proposed a TOF system for PID, the base technology, a single photon sensitive detector capable of 10 picosecond timing can be used in a variety of other applications, such as in a RICH, Time-of-propagation detector, or as the start counter. Thus, our studies, if approved, could have wider applicability than detailed in this proposal. The following shows our 3-Year plan of study, including the timeline for when we expect to have these studies done.

Year 1 Plans

In the first year, the UIUC High Energy Physics engineering group will develop a readout board which incorporates the PSEC5 ASIC. The PSEC5 is expected to be available starting in the summer of 2014. The electronics we ultimately develop should be capable of satisfying all the requirements for electronics at a collider with near deadtime-less performance, i.e., a multi-event buffered, parallelized pipeline readout. The trigger latency supported should be ~4 microseconds. This initial year, however, the goal will be to develop an initial version of this board which can support testing of MCP-PMTs, without all of the features necessary for a collider capable readout. This will allow for a period to gain familiarity with the PSEC5 ASIC, debug any problems that result, before adding in multi-event buffering and parallelized pipeline readout. The requirements of the DAQ for an EIC detector will also be explored, which should solidify the specifications that will be needed for trigger latency and event rates in a collider environment.

In parallel, we will develop the radiator and detector design, exploring how to optimize the performance and cost of the fused silica radiator as well as the generic issues with the placement of a TOF wall, which one prefers to have at normal incidence to direction of the outgoing particles. We will test various fused silica from different vendors to determine the best performance for the cost. We will also do a simulation of various physics observables to determine the detectors full performance requirements, and particularly how they interact with other proposed tracking and PID detectors at the EIC.

The major milestones we hope to achieve in the first year are:

- Study and simulate the primary physics channels which we think are the most interesting that would be enabled by particle identification. This could be measurements of kaons to determine Δs, but we want to also broaden the studies currently done to ensure that our design can accommodate as much of the interesting physics that is possible at the EIC.
- Come up with a TOF PID detector design that satisfies these physics requirements, including the size and shape of the Cerenkov radiators, and how to enable a projective geometry from the 8”x8” tiles. We will also calculate and optimize the expected number of photoelectrons from a typical particle to maximize the performance of the timing measurement, within reasonable limits on the cost.
- Acquire and test different Cerenkov radiator designs and from different manufacturers. We anticipate using fused silica, but will test different samples to find the cheapest manufacturer that delivers the needed performance.
- Acquire PSEC5 ASICs and design a readout board around this. This first version of the board should be capable of supporting standalone readout of MCP-PMTs via Serial, Ethernet or USB, and

should represent the first step to a fully functional readout for a collider application such as at the EIC.

Year 2 Plans

We expect to receive the first pieces of MCP-PMT tiles from Incom at the beginning of January 2015. Since this will be the first time that these tiles have been tested, there will be much work required to characterize them. In particular, we will proceed to test the Incom LAPPD tiles for the main issues that we have identified, such as the timing capabilities, the rate capabilities, the aging effects, and the ability to operate in a magnetic field. These tiles will be initially characterized via lasers to establish a baseline for performance, and then mounted into a TOF system with the Cerenkov radiators and electronics for testing in a cosmic ray test stand. We will also test the tiles in the high field test magnet at BNL, and then finally in the test beam at FNAL.

For the second year, UIUC will develop the next revision of the electronics to the level that it can be fully functional in a collider environment. One possible plan is to use PHENIX as a test case, so that the electronics would be capable of being integrated into the PHENIX detector readout. However, the design will be left generic enough that with a redesign of a few modules, it could be incorporated into any of the conceivable EIC detectors.

Below, we summarize our milestones for the second year, along with some of the major concerns for us to test:

- Timing Performance: We want to demonstrate timing performance at the 10 picosecond level or better. This will be done initially with laser studies, then from cosmic ray studies, and finally in test beam.

- Uniformity: We want to demonstrate uniform effectiveness across the MCP-PMT. This can be done with laser scans, cosmic rays, and in test beam.

- Quiescent Noise: LAPPD claims less than 0.1 Hz/cm^2 of background noise. We want to determine the noise rate for the Incom produced tiles, and ensure that they are below the rate needed at an EIC detector.

- Rate Capability: We want to determine the rate capability, and that they satisfy the requirements of an EIC detector.

- Aging: We want to determine the aging characteristics of the Incom produced MCP-PMTs. Since this is potentially destructive to the MCP-PMT, we may perhaps defer this test to the LAPPD collaboration.

- Operation in a Magnetic Field: We want to determine the effects of a magnetic field on the operation of the MCP-PMT, particularly for the case where the field is transverse to the pore axis. Can the effects be mitigated by increasing the HV bias on the tube? If it is determined that we can use lasers or cosmic rays to do this test, then this testing can be done at the test magnet facility at BNL or perhaps in other locations. Otherwise, we will have to arrange for a magnet at a test beam facility.

- We hope to build the second and final revision of the readout electronics, one that is fully buffered and parallel-pipelined, so that it can be used at colliders.

Year 3 Plans

In year 3, we envision improving on the design based on the lessons from the second year, and come to final design decisions, which we will test. We envision that there will also be many opportunities for new ideas to extend the abilities of these Incom LAPPD MCP-PMTs, such as coating the top MCP with CsI photocathodes, which would provide better sensitivity to UV and thus better performance for Cerenkov light.

Budget

Included in our budget is a single post-doc salary, split between UIUC and UMass, with each post-doc contributing half their time to this project. We also include funding for the UIUC High Energy Engineering lab to develop the readout card based on the PSEC5 ASIC. The post-doc's are placed where they can contribute the most. Illinois will be where the readout electronics would be developed, and the close proximity of Incom to UMass-Amherst will allow for frequent consultation with the MCP-PMT manufacturer.

	Year 1	Year 2	Year 3
Personnel			
0.5 FTE UIUC post-doc	$50,000	$50,000	$50,000
0.5 FTE UIUC Electical Engineer	$71,000	$71,000	
0.5 FTE UIUC Technician	$50,000	$50,000	
0.5 FTE UMass post-doc	$50,000	$50,000	$50,000
2 Summer students, Howard U	$12,000	$12,000	$12,000
2 Summer students, Muhlenberg	$12,000	$12,000	$12,000
Travel Costs			
Travel	$10,000	$10,000	$10,000
Beam Test (FNAL)		$15,000	$15,000
Equipment			
PSEC4 Readout Test Boards	$10,000	$10,000	
Incom LAPPD 8"x8" MCP-PMTs		$120,000	
Totals	$260,000	$395,000	$144,000