Project Engineering and Design for ePIC pfRICH of Laser Monitoring System

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Introduction

The DOE CD-2/3 Review in 2025 will evaluate the readiness of all ePIC detector systems (including the Particle Identification ones) for the start of the construction phase. In preparation for the Final Design Review of the proximity-focusing Ring Imaging Cherenkov detector (pfRICH), we propose to build the laser monitoring system at Brookhaven National Lab. This Project Engineering and Design (PED) is to demonstrate the capability of such in-situ monitor system, by measuring the diffused laser light profile and coverage, achieving the desired time resolution. The system operation parameters will be estimated and documented.

1 Design and Requirements

The ePIC pfRICH detector utilizes aerogel tiles as a Cherenkov radiator medium for ring imaging purposes. The overall pfRICH layout is shown in Fig. 1.

For the most part of the pfRICH acceptance, the Cherenkov photons produced in aerogel are directly hitting the sensor arrays. However, for the charged particle tracks close to the pfRICH acceptance edge, a set of mirrors is needed to reflect the Cherenkov photons away from the side walls towards the detection plane.

The optimal configuration to achieve this is to have mirrors in the shape of an outer truncated cone (becomes narrower in the electron-going direction) and an inner truncated cone (becomes wider in the electron-going direction), see Fig. 1. The outer truncated cone consists of twelve mirror sectors (with a concave reflecting surface) and the inner truncated cone consists of four mirror sectors (with a convex reflecting surface).

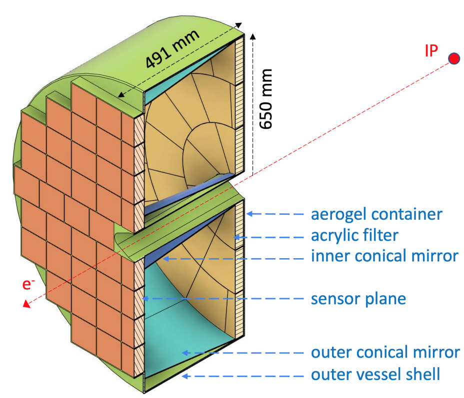

Figure 1: pfRICH detector layout.

Focusing is not needed to achieve the required pfRICH performance. This fact relaxes the requirements greatly, effectively reducing them to achieving a specified level of reflectivity when coating non-focusing substrates of a given shape.

GEANT simulations suggest that the detected photon wavelength of interest for the pfRICH is $\lambda > 300$ nm, despite the fact that the Cherenkov photon is produced at a lower wavelength. Smaller wavelengths are suppressed by absorption and Rayleigh scattering by the aerogel material itself. Besides this, a strong aerogel refractive index dependency on the wavelength $n(\lambda)$ in the near UV range causes a track-level reconstructed Cherenkov angle degradation if these photons are accounted for.

Because of this, there will be an acrylic filter with a wavelength cutoff $\sim 275 - 300$ nm installed between the aerogel and the photosensors, see Fig. 1.

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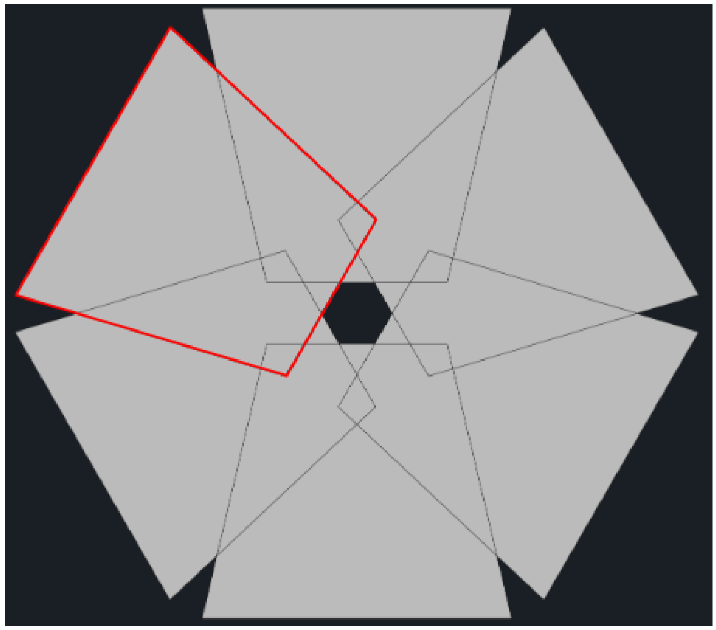

Figure 2: Laser coverage overlap map (in x-y axis) from with six fiber-diffuser sources at the HRPPD sensor plane. The source-to-center plan distance is 45 cm. Note that the combined profile fully encloses the sensor place disk (100 cm). The photon path from the outer and inner mirrors are not taken into consideration in the layout.

Besides providing the PID in the electron beam direction, the pfRICH is expected to provide the time of flight information with less than 100 p timing resolution. It is critical to have an independent verification/source to cross-check the single timing profile and integrity to minimize the timing jitters during the operation caused by detector instability or readout delay during the operation

1.1 Need for A Laser-Based Monitoring System and Tentative Design

A laser-based system is proposed to monitor the pfRICH performance throughout its operational life. The purpose is to measure both the single photon timing resolution as well as keep track of the pulse height amplitude as a function of time. Each characteristic is critical to the success of the detector's ToF and ring imaging capabilities, respectively. To measure the timing resolution, an array of fibers are introduced inside the detector volume from the aerogel side which cast a broad profile of low intensity light onto the sense plane such that each HRPPD pixel accumulates some number of single photon hits after a given number of laser pulses. The distance between a given fiber tip and an HRPPD pixel defines the flight time for photons emitted from this fiber, hence the distribution of reconstructed flight times will reveal the timing resolution for this single pixel. Similarly, a separate array of fibers are arranged such that emitted photons reflect off of the outer mirror surface before impinging the HRPPDs. In this case, the amplitude of the measured signal is monitored for any degradation over time, which would indicate the deterioration of either the photocathode quantum efficiency or mirror reflectivity, or both.

The pfRICH monitoring system employs a picosecond (”Pilas”) laser which produces a 405 nm laser beam with a ~ 45 ps pulse width. The beam is coupled to a custom fiber-based 1×14 splitter, as shown in Fig. 4 that evenly distributes the beam energy into arrays of fibers routed into the detector vessel. One set of six strategically placed fibers serves as an extended light source to directly illuminate the HRPPDs and provides a measure of the timing resolution. A second set of fibers emit photons that mostly experience a single reflection off of the mirror surfaces before hitting the sense plane to gauge the reflectivity. A custom-sized $5\ mm \times 5\ mm$ engineered diffuser is used to optimize the intensity profile emitted from each fiber, as seen in Fig. 2. Additionally, a fiber delay line is added to each fiber branch to allow the ability to easily separate out in time photons originating from a given fiber. In all, there are three sets of fibers downstream of the splitter which deliver photons from the laser

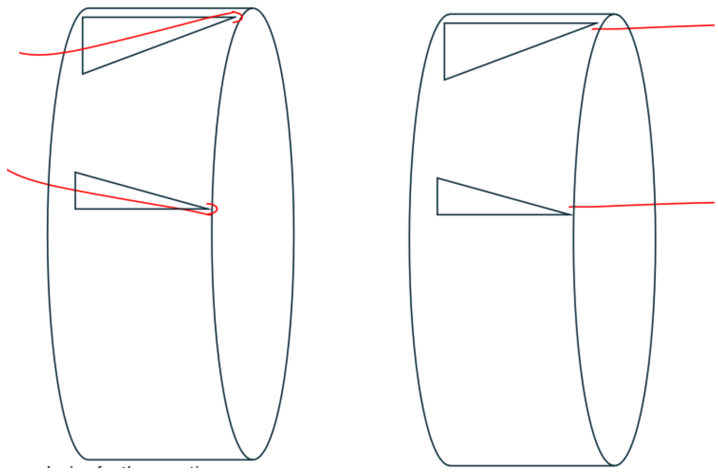

Figure 3: Potential fiber path, in both pictures, the sensor plane is on the left side of the cylinder.

to the detector vessel: delay fibers, long extension fibers, and fibers mounted permanently inside the detector vessel. The exact mounting scheme and location including the optimal fiber path are to be finalized - possible fiber paths being explored are shown in Fig. 3. Finally, multiple fast photodiode sensors are used to sample the laser light before and after the splitter for the purpose of monitoring the light output intensity and the timing performance. Most of the detailed hardware items for the full system have already been identified, including the fiber patch panel connectors.

1.2 Monitoring System Experiences at Brookhaven National Lab

The group at Brookhaven National Lab has spent the last five years developing a laser based calibration system for the sPHENIX Time Projection Chamber (TPC). The so-called "Diffuse Laser" system is physically very similar to the system proposed for the pfRICH. Like the pfRICH, an array of fiber optical cables deliver pulsed laser light to the inner volume of the detector vessel for the purpose of gauging the detector response. In the case of the TPC, however, the fibers are rated to carry high intensity UV photons for the purpose of liberating photoelectron clusters from photocathode strips positioned on a focal plane facing the fibers. Though the purpose for injecting light into the TPC differs from the case of the pfRICH, the overall geometry of the two laser systems are quite similar. Light emitted from the fibers in each system is also diffused using a specialized diffuser mounted just downstream of the fiber tip. In both cases, the generated intensity profile is carefully engineering to elicit a response from a known reference. A major advantage of the pfRICH laser system is the fact that the challenge of delivering high power UV photons is absent; this was a major obstacle for developing the TPC laser system. Despite these challenges, however, the BNL group successfully assembled and commissioned the TPC Diffuse laser system and it is currently providing calibration data for the TPC during the RHIC 2024 run.

2 Evaluation Criteria and Verification

This PED is conducted for the purpose of demonstrating the viability of the proposed scheme for monitoring the pfRICH single photon timing resolution and signal amplitude per readout pixel over the lifetime of the experiment. We expect to accomplish this by completing the following objectives:

1. Measure the light yield and profile from the splitter-diffuser combination (the setup used for this measurement is briefly described in Fig. 5 and 6)

2. Extract the effective timing resolution, which includes the laser pulsing structure, HRPPD timing, any time dispersion resulting from the 25 - 30 m long fiber optical cables and/or optical elements, etc.

3. Estimate data footprint and propose optimal running parameters during operation

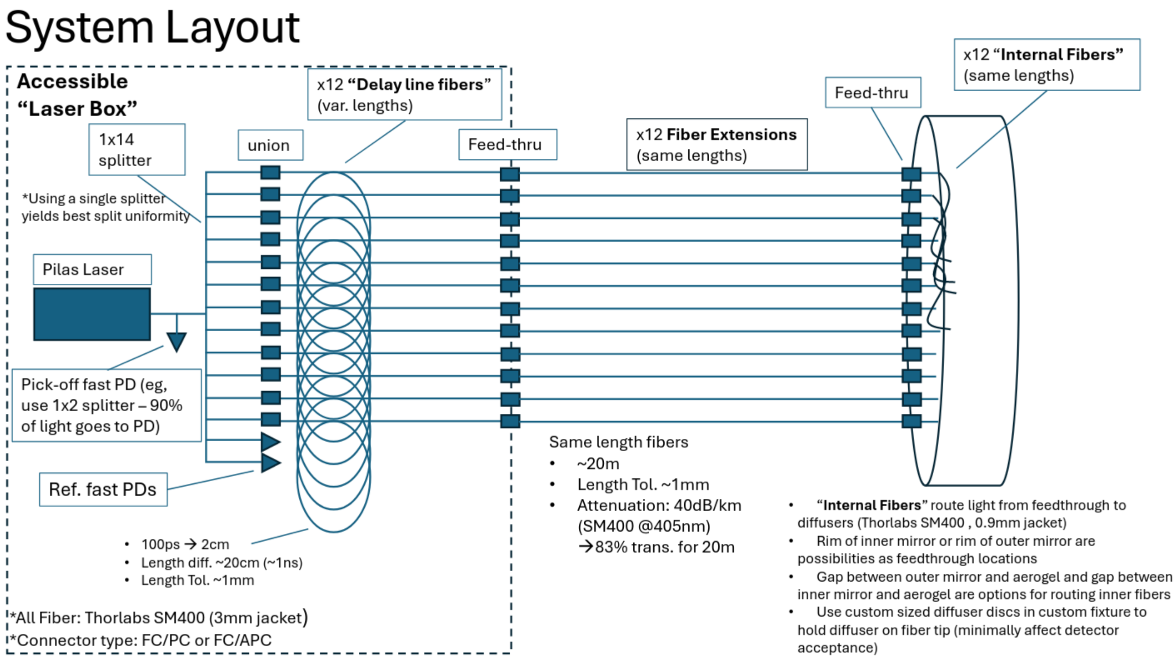

Figure 4: System layout Schematics.

4. Demonstrate the long-term operation and stability

The outcomes will be documented in the form of a report as part of the PED conclusion.

3 Milestones and Deliverables

To track the progress of the proposed project, the following milestones, and deliverables are foreseen:

1. Sep 2024: determine the minimum bending radius of the optical fiber in an effort to minimize the overall design footprint of the fiber apparatus inside the detector vessel (done at BNL)
2. Sep 2024: in parallel, use a ray tracing program (TracePro) to verify the proposed opening angle spec for the diffused intensity pattern will provide the expected coverage on the HRPPD sense plane. This must be done before purchasing the diffusers, which are an expensive line item due to the minimum order quantity (MOQ) - see Table 1. (done at MS by student and at BNL)
3. Oct 2024: equipment purchase followed by assembly and initial tests of fiber optic configuration, including measurements of attenuation in the full optical path and confirmation of the ability to deliver relatively small bunches of photons in a given fiber with the expected timing structure (done at BNL)
4. Dec 2024: demonstrate the readout chain of the HRPPD, ASIC (HGCROC) and DAQ computer configuration (done at BNL)
5. Jan 2025: initial validation of the diffused intensity profile and signal amplitude of the laser-splitter-diffuser-HRPPD configuration/setup, including initial timing resolution measurements (done at BNL)
6. March 2025: a student from Mississippi State will travel to BNL to measure the diffused light pattern from multiple fiber branches, including the intensity deviation in each branch and will do a more detailed study of the timing structure of photons emitted from each branch
7. June 2025: implement a realistic diffused light pattern and time structure into the EIC GEANT4 simulation and generate a report on the PED findings regarding the laser system, including timing resolution, diffused pattern, recommended parameters, and the estimated data size during the operation (done at MS)

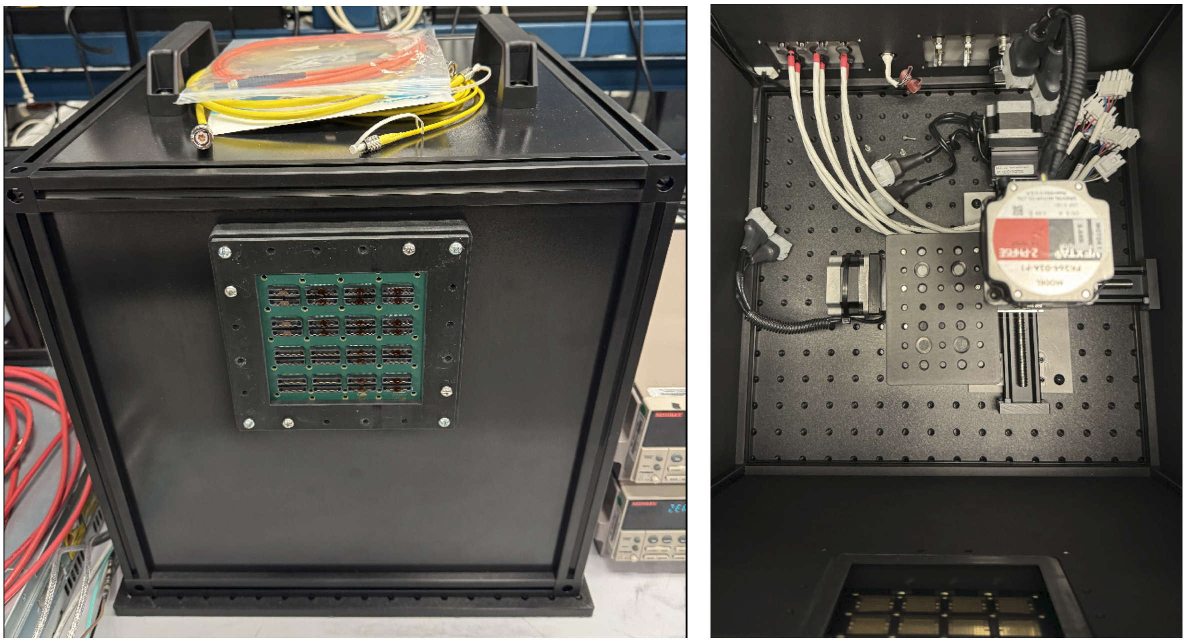

Figure 5: Left: dark box with inner length and width of 40 cm × 40 cm. Right: an inside view of the dark box.

8. June 2025 (optional): incorporate a scaled down version of the monitoring system (consisting of 2 to 4 fiber source points) in the pfRICH prototype, which is planned to be constructed in early 2025. This is for the purpose of testing our assembly techniques, validating the monitoring system performance in a realistic setup, and measuring the impact of the fiber footprint (in terms of obstructing a portion of the Cherenkov signal) during the planned Fermilab beam test in the Spring (done at BNL/Stony Brook Univ.).

4 Resource Request

The funding required to support this PED proposal is almost $36,000 in total, which reflects the total material cost only as the labor and overhead costs amount to $0 - see Table below. As part of the Mississippi State Contribution, the overhead for the facilitation of the hardware purchase of this PED is $0. Additionally, the machine and electronic shops at Mississippi State will cover the necessary labor costs for part manufacturing.

It is important to point out that roughly all of the materials purchased under this proposal, if determined to be adequate for this application, will be reused for the final system and account for a major fraction of the total system cost. The additional cost to complete the full system is mainly driven by the purchase of additional fiber and interconnects in the final detector vessel, which, under current pricing, is estimated to amount to about $20,000 - $30,000.

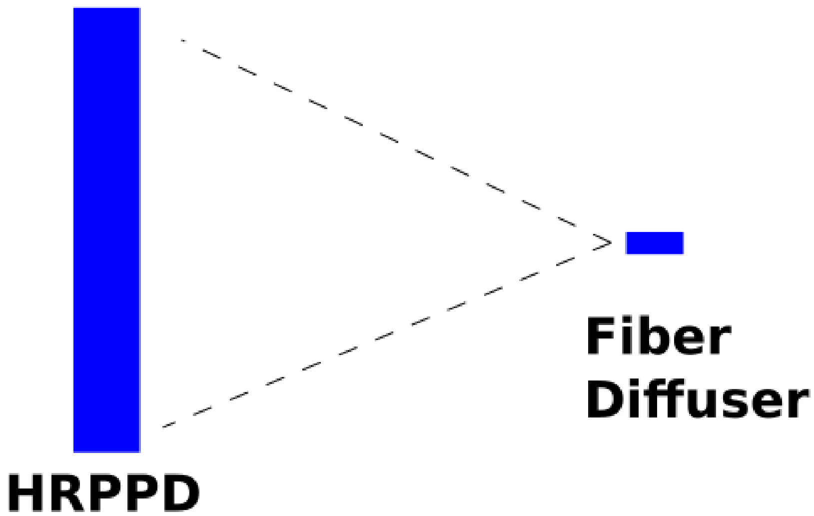

Figure 6: Left: dark box with inner length and width of 40 cm × 40 cm. Right: an inside view of the dark box.

Table 1: PED budget request for ePIC pfRICH Laser Monitoring System.

	Quantity	**Unit Price ($)**	**Total Price ($)**
NKT Photonics Pilas 405nm Laser (PIL040-FC)	1	15,349.10	15,349.10
Fiber	6	200.00	1,200.00
Thorlabs Fiber-Splitter	1	3,600.00	3,600.00
50 deg. custom-sized diffuser + fixturing	40 (MOQ)	98.00	3,920.00
Fast photodiode sensors	2	4,000.00	8,000.00
FC/APC patch panel connectors/feed-throughs	6	58.00	348.00
Laser Box (for containing laser head and fiber optics)	1	1000.00	1,000.00
Misc. items, consumables	1	1,000.00	1,000.00
Machine shop time	40 hrs	0.00/hr	0.00
TracePro Software Licensing (1 Year)			1,500.00
Total	–	–	35,917.10
Overhead	0	0	0
Total with overhead	–	–	35,917.10