RICH DETECTOR PROTOTYPE FOR THE EIC FORWARD DETECTOR

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Abstract

An R&D program is proposed to build a Ring Imaging Cherenkov Counter (RICH) prototype, to be used for the particle identification up to the momentum of 10 GeV/c in the EIC forward region. Innovative techniques of photo-detectors and aerogel radiator will be exploited. The forward RICH requires the detection of single photons on large surfaces, with high time and space resolutions, insensitivity to magnetic fields, high quantum efficiency in the visible and close to ultraviolet wavelength region, limited and uniform radiation length over the entire detection surface, and a limited total geometrical length of the whole detector. In particular two innovative techniques will be applied to this prototype of proximity focusing RICH detector: aerogel block radiators with varying refraction index and a detector plane for Cherenkov photons assembled with silicon photomultipliers (SiPM).

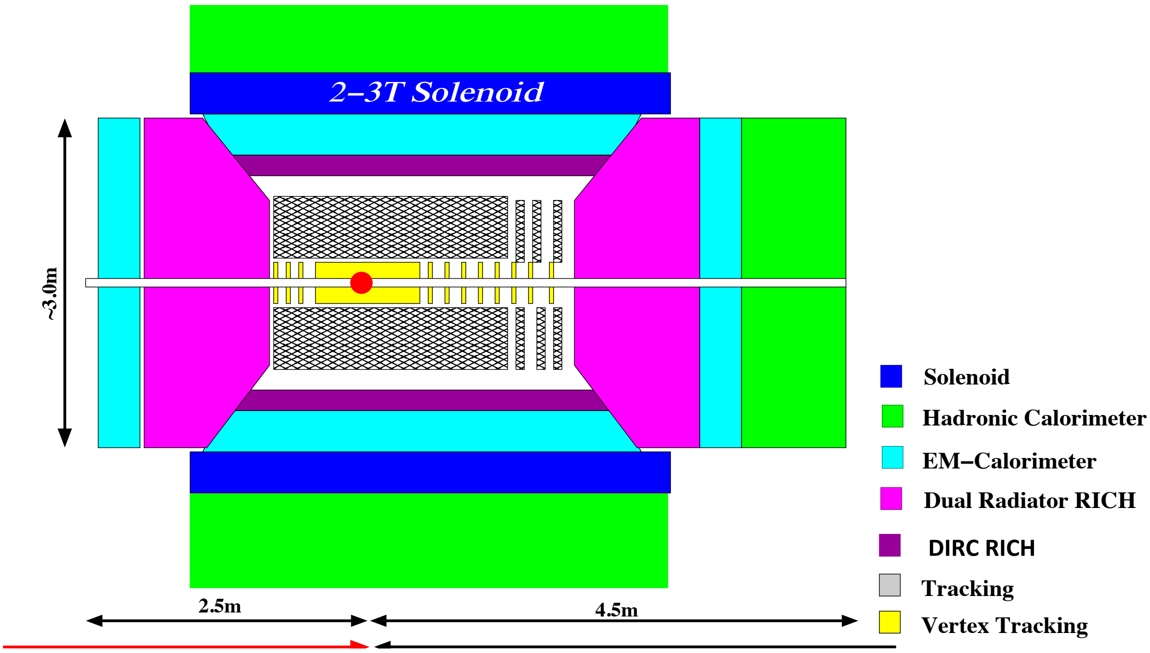

Figure 1. A schematic view of a dedicated EIC detector.

Motivations

Experiments with identified strange hadrons can provide important information on several hot topics in hadronic physics: the strange distribution and fragmentation functions, the nucleon tomography and quark orbital momentum, accessible through the study of the generalized parton distributions and the transverse momentum dependent parton distribution functions, the quark hadronization in the nuclear medium and the hadron spectroscopy. Thus the kaon identification is crucial in the design of the EIC detector and a Ring Imaging Cherenkov

(RICH) detector is proven to be a powerful solution to enhance the particle identification capabilities and make EIC a unique facility for studying the physics topics summarized above (see Fig. 1 [1]).

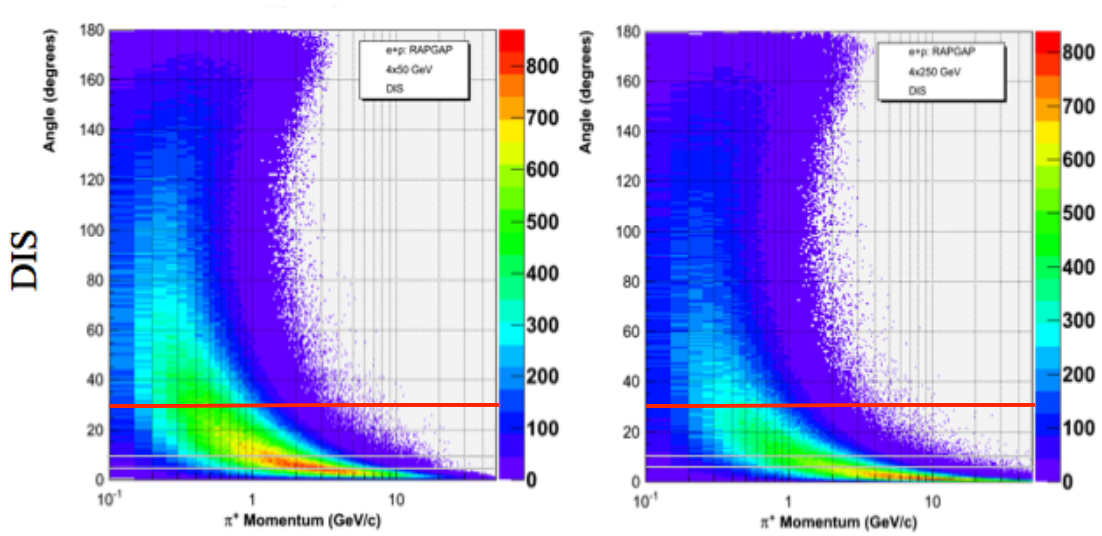

Figure 2. Scattering angle vs. momentum in the laboratory system for pions for SIDIS events. The left column is 4x50 GeV and right column is 4x250 GeV collisions. The electron beam is moving towards 180° and proton beam is moving towards 0°. The red line indicates the approximate transition from the central to the forward EIC region.

The ion side endcap of the EIC detector would have to deal with hadrons with a wide range of momenta. Figure 2 presents the scattering angle versus the momentum in the laboratory system for pions for the diffractive processes and SIDIS events [1], while Figure 3 presents the kaon/pion ratio distributions.

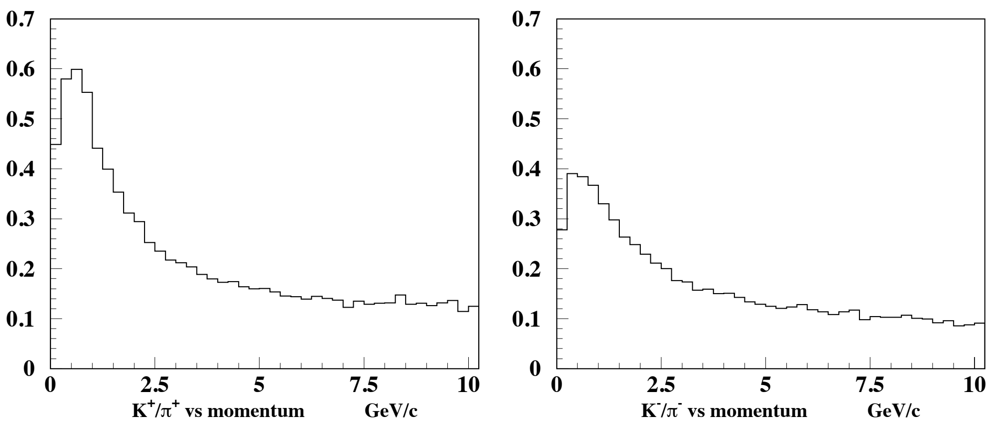

Figure 3. Kaon/pion ratio vs. momentum in the laboratory system for SIDIS events in the forward region.

The distribution in Fig. 2 shows that kaon identification up to 10 GeV is highly desirable in order to fully explore the power of SIDIS experiments. Moreover, from Fig. 3 we can see that pions greatly outnumber kaons at nearly all kinematics. Thus an aerogel RICH detector can tremendously reduce the backgrounds for the detection of unstable particles that decay to at least to one charged non-pion. The forward RICH could include a dual radiator: aerogel (perhaps with more than one index of refraction) to discriminate pions from kaons up to the momentum of 10 GeV/c and a C_4F_{10} gas or equivalent to extend the response to higher momenta. Moreover, as we can see from Fig.3, the K/π ratio for momenta greater then 2.5 GeV/c is of the order of 0.1-0.15. Thus a 4σ K/π separation is needed and this is the requirement for the proposed RICH.

The presence of a strong magnetic field limits the choice of the possible photon detector. Most of the RICH counters in operation so far are based on gaseous detectors or photomultipliers for the detection of the Cherenkov light. A RICH counter based on the detection of photons with solid detectors has not yet been constructed. However the recent progress in single photon detection by the silicon photomultiplier is of considerable interest.

In this proposal we suggest to investigate the possibility to build a RICH with an aerogel radiator and a new type of Si photon-counting device (SiPM) insensitive to the magnetic field.

Ring Imaging Cherenkov Counters Overview

Detectors that can image Cherenkov rings, called Ring Imaging Cherenkov Counters (RICH), represent a powerful tool in identifying charged particles produced in nuclear and sub nuclear interactions in a wide range of energies. Their performance allow to measure with extremely high precision the speed of particles, through the detection of the Cherenkov light that accompanies their passage in a dense mean with a velocity larger than the velocity of light in the same mean. The technologies developed up to now in order to detect single photons on wide surfaces, up to sizes of tens of squared meters, have been based on the mechanism of photoemission in photosensitive vapors (TMAE, TEA), or on thin films of CsI and successive amplification of photoelectrons in gaseous mixtures. The gas photo-detectors represent still today the optimal solution for RICH detectors that operate in presence of magnetic fields. However they suffer from important limitations in their performances due to the high-energy threshold of the photosensitive materials, due to the remarkable chromatic aberration of the Cherenkov radiators in the ultraviolet region, and due to the intrinsic characteristics of the amplification processes and of the transport of photoelectrons in gases. These limitations decrease the ability to identify high momentum particles in experiments at high intensities. Therefore, to follow the pace of the increasing energy and luminosity of accelerators, there is the tendency [2] to project and study photo-detectors which are fast, with a high time resolution and that operate in the region of visible and near-ultraviolet light, to take advantage of the light wavelength region where the optical properties of the materials are more favorable (higher transparency and lower chromatic aberration). This wavelength region results in the detection of a larger number of Cherenkov photons with a reduced angular dispersion. The use of devices that detect the visible light offers also the advantage to increase the number of the materials that can be used as radiators, allowing building RICH detectors with performances unexpected a few years ago. In particular, the detection of light emitted in silica aerogel has to be considered (see Fig. 4). Silica aerogel is the only existing solid radiator with a refractive index between those of liquids and heavy gases, which allows to identify particles with momentum in the range between 1 and 10 GeV/c. Several experiments in the world have already demonstrated the good performance of aerogel as solid radiator in Cherenkov detectors for particle identification. Examples are the threshold detector in BELLE [3] (at the KEK B-Factory) and the RICH detector of HERMES [4] and LHCb [5].

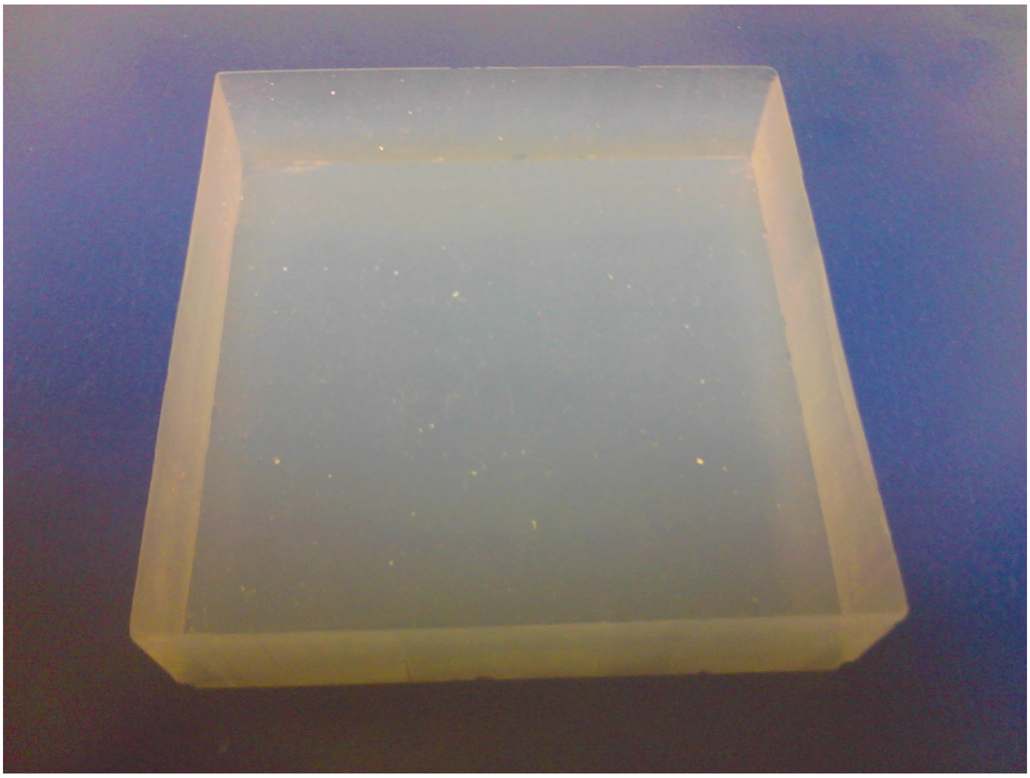

Figure 4. 10x10x3 cm^3 aerogel tile.

Goals of the Project

The present project aims to demonstrate the potentiality of a novel type of RICH detector based on aerogel radiator and SiPM photon-detector, which is suitable for the EIC detector with a potentially broad field of applications.

High angular resolution in RICH detectors is typically obtained with the help of spherical mirrors, which focalize the light cone. In the case of proximity focusing detectors, having the advantage of taking a very limited space, the thickness of the radiator is an intrinsic limit to the angular resolution. To overcome this problem, the use of a radiator with variable refraction index has been recently proposed, for applications at the future Super B-Factories; it is made by the superposition of layers of aerogel with increasing refraction index, producing a self-focusing ring [6]. A further improvement, which is at the origin of this proposal, can come from the use of monolithic aerogel tiles, with refractive index variable in steps, as those recently produced by the Boreskov Institute of Catalysis in Novosibirsk [7], or with a gradient [3]. The advantage is to avoid the light losses due to reflection and scattering at the surfaces of each single layer, and the possibility to have inside the same tile thin regions of different refraction index, while the single layer thickness is limited by the mechanical properties of aerogel. This kind of aerogel has not yet been extensively studied and scarcely tested with particle beams.

The relatively low photon yield in the thin aerogel layers requires maximizing the quantum efficiency of the photon detector. Rayleigh scattering of ultraviolet light inside the aerogel reduces the accuracy in the measurement of the Cherenkov angle [8] and demands for the extension of the photo-detector quantum efficiency into the visible region. Silicon photomultipliers are a new type of photon-detector, which satisfies these requirements and offers the important advantage to be insensitive to the magnetic fields, something crucial in the EIC environment.

The SiPM is a new type of photon device made up of multiple avalanche photodiode pixels operated in Geiger mode. The main features of this device are as follows:

- high sensitivity to the single photoelectron signal;
- room temperature operation;
- low bias (below 100 V) operation;
- high gain (up to 10^6);
- insensitivity to magnetic field;
- excellent time resolution and space resolution;
- high quantum efficiency in a wide range of wavelengths from the visible to the ultraviolet;
- high photon detection efficiency for light with wavelength 300-900 nm;
- newly developed SiPM arrays (4x4 and 8x8 with 3x3 mm^2 individual elements, see Fig. 5 and 6);
- small thickness and limited material budget.

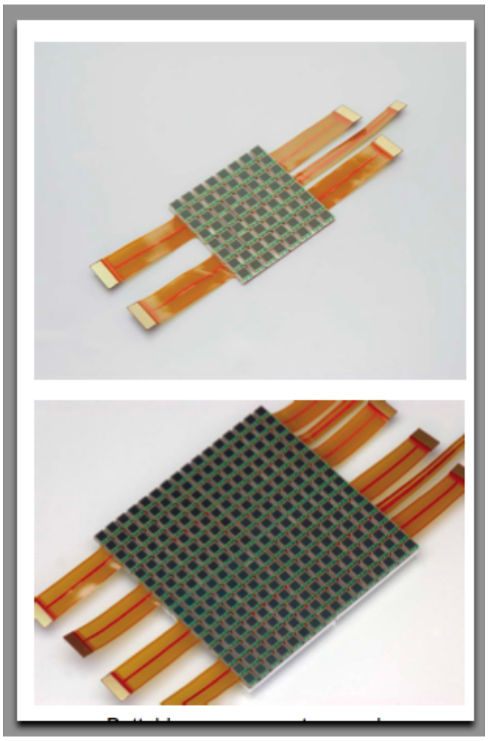

Fig. 3. SiPM 8x8 and 16x16 arrays with 3 mm^2 active area elements. Their structure minimizes gaps between elements.

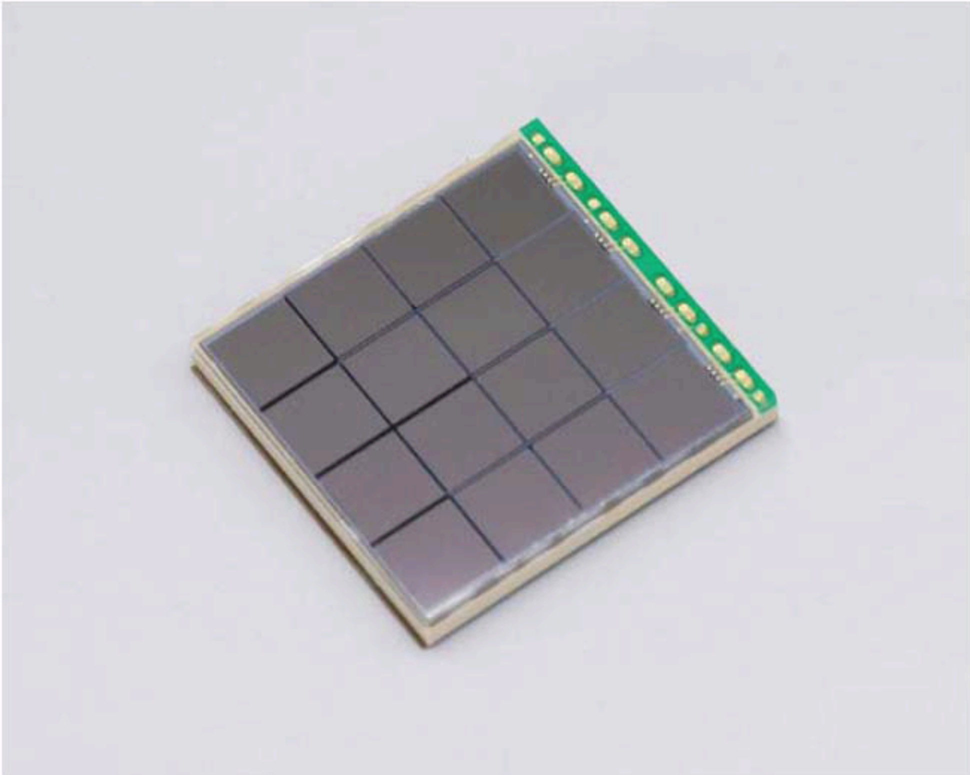

Figure 6. A monolithic SiPM array which minimizes the not-active area. It demonstrates the flexibility and compactness of such devices in fast progress.

The use of SiPM could have a large impact for RICH detector in the next future, as they are compact and robust devices with a fast decreasing price. The intensity of the dark noise is the current main limiting characteristic of these photo-detectors but there is a strong commitment by the producers to reduce it significantly. Noticeably, SiPM good timing properties (at the level of a few hundreds of picoseconds) [9] will allow the use of trigger time windows of only ~5 nanosecond, necessary to reduce the high dark noise of these photo-detectors. The radiation hardness has to be studied in details as well following the rapid progress in the production technologies. However, tests made by the Belle collaboration showed that SiPMs could easily handle neutron flux of about 10^9 n/cm^2 without any deterioration in the characteristics of the signal [2].

The proposed R&D will include the following items.

- MC simulation of the proposed RICH prototype.
- Studies of the properties of monolithic tiles of aerogel made with layers of different indexes of refraction, with a auto-focusing configuration to be used as radiators of a proximity focusing RICH. Based on test results, it will be determined the Cherenkov angle resolution that can be obtained, and it will be studied, with the help of simulations, the optimal prototype configuration.
- Studies of the SiPM characteristics such as:
    - photon detection efficiency versus wavelength;
    - pulse height resolution in the region of low number of photoelectrons;
    - time resolution for one-photoelectron signals;
    - dark rate;
    - temperature dependencies of the signal;
    - radiation hardness.
- Design of a power supply card with programmable bias voltage to equalize the SiPM response.

- Design of the fast multichannel front-end electronics, completed of a fast SiPM preamplifier with excellent timing characteristics for one-photoelectron signals.
- Study of the light collector option for the SiPM arrays.
- Cosmic ray test stand that will allow to check the main characteristics of the proposed prototype.
- Test of the prototype with hadron and electron beams in order to verify and improve the performance of the whole detector, including radiator, photo-detector, power supply, preamplifier, front-end electronics and data acquisition.

Results of the research, their interest in the advancement of knowledge and any potential applications

The ultimate result of this research is to prove the feasibility and the proper functioning of the proposed detector when exposed to particle beams. This detector is essential in experiments, which require a particle identifier (PID) very compact, with a wide surface, able to afford high counting rate, insensitive to magnetic fields, resistant to radiation.

The proposed detector exploits the properties of multilayer aerogel radiators and of SiPM photo-detectors (Geiger-mode APD). These are immune to magnetic fields, have a high detection efficiency for photons (single photons in particular), are easy to use, are potentially cheap, and do not require high voltage power supply. Aerogel radiators with variable refractive index has the advantage of producing more Cherenkov light without enlarging the relative ring in the focalization plane.

R&D Timeline

• *Year 1*

The first part of the project is intended to study and design the RICH prototype and to test and select the most promising components.

1. Simulation of the proposed prototype will be done to estimate the optimal geometry, possible velocity resolution and background contamination. The software will be written for the pattern recognition and event reconstruction.
2. The commercially available SiPM with the required space, time and noise characteristics will be identified.
3. The requirements for the aerogel radiator with the needed characteristics will be chosen.
4. Samples of the main components of the detector (aerogel and SiPM), commercially available, will be acquired, and their characteristics will be studied in the laboratory.
    - For aerogel, at the wavelengths of interest, we will measure the transparency of the various samples, their contributions to the absorption and to the Rayleigh scattering, the refractive index, its uniformity along the sample surface and its variation with depth.
    - For SiPM it will be measured the variation of gain and background noise with temperature and supply voltage, their response to different wavelengths (quantum efficiency), the linearity under the few photons regime, the timing of their response to picosecond pulsed light sources, and their resistance to radiation.
5. Studies will start also to identify the front-end electronics for providing the bias voltage to and reading the SiPM photodetectors with programmable parameters. These studies will detect the timings that could be obtained with the existing chips, and will design a FPGA (Field Programmable Gate Array) with a complete software managing data processing and communication with a PC.
6. The design of the light tight mechanical box equipped with connectors for the passages of an inert gas (needed in case of hygroscopic aerogel) and for the electric cables will be provided.

7. The trigger counters, to be used in the beam tests, placed before and after the prototype will be designed.
8. The tracking detectors to measure the parameters of the particle track with the millimeter resolution will be identified.
9. The funnels to convey the Cherenkov light will be designed.
10. The DAQ system will be designed and all components will be acquired.

• *Year 2*

The central part of the project is intended to the procurement of the selected components and to the assembling of the RICH prototype and cosmic test.

1. Acquisition of the selected components.
2. Purchase of the SiPMs of the type chosen.
3. Purchase of the front-end electronics and DAQ.
4. Purchase of the aerogel tiles.
5. Realization of the light conveyors (if needed).
6. Assembling of the RICH prototype complete of:
    - the light tight black box with all cables and connectors;
    - the aerogel radiators;
    - the SiPM detectors;
    - the light emission diode (LED) calibration system;
    - the front-end electronics;
    - the DAQ system;
    - the trigger counters;
    - the tracking detectors;
    - personal computer for DAQ and data analysis.

7. Commissioning of the cosmic test stand.

• *Year 3*

The last part of the project is intended to measure the performance of the RICH prototype using test beams of different particles. We will run different types of selected aerogel, we will analyze the data taken, and, from their interpretation, we will optimize the performance of the RICH.

Management plan

Funding request and Budget.
We request a total $298K over a three-year period, as indicated in the table below.

	Year 1	Year 2	Year 3	Total
Postdoc	$45K	$46K	$47K	$138K
Hardware	$38.5K	$61K	$14.5K	$114K
Travel	$14K	$15K	$17K	$46K
Total	$97.5K	$122K	$78.5K	$298K

Procurement

Year 1 – base equipment, commercially available SiPM elements and aerogel tiles, standard electronics for component tests and front-end-board design:

1. Personal computer and other staff for postdoc: $2.5K
2. SiPM elements: $4K
3. Electronics for front-end-board prototype and SiPM tests: $11K.
4. Standard aerogel tiles: $3.5K
5. Black box design: $2.5K
6. DAQ electronics (flash ADC and TDC): $12K

7. Low voltage: $3K

Total $38.5K

Year 2 – equipment core, RICH prototype structure, selected SiPM arrays and aerogel tiles, dedicated front-end-boards:

1. Black box and structure: $5K
2. SiPM arrays: $15K
3. Aerogel tiles: $10K
4. Front-end-board prototype: $6K
5. DAQ electronics: $15K
6. LED calibration system; $2K
7. Temperature control system: $8K

Total $61K

Year 3 – optimized equipment for best performances:

1. SiPM arrays: $4K
2. Multilayer aerogel tiles: $5.5K
3. Front-end electronics: $5K

Total $14.5K

Responsibilities

Following the R&D outline the main responsibilities of the US part (Jlab, CNU, Argonne Lab) are listed below.

- To perform the simulation and design of the RICH prototype. To carry out these tasks, a postdoc will be hired.
- The prototype assembling at Jlab.
- The mechanical light tight box design to host the RICH prototype, with passages of cables and gases.
- The construction of two trigger detectors with fast scintillator and tracking system, necessary to measure the particle trajectory.
- The data acquisition system.
- The development of a dedicated software for the data acquisition and the off-line analyses.
- The characterization of the SiPM photodetectors.
- The study of light conveyors to reduce the dead area influence on the photodetector.
- The participation in the prototype tests.

The primary responsibilities of the Italian part of the collaboration (INFN) will be:

- To acquire mono and multilayer aerogel samples, to perform the optical measurements for their characterization in terms of transparency, and measurements of refractive index.
- To study the characteristics of the SiPM photodetectors, such as the quantum efficiency, the robustness to high luminosities, the insensitivity to magnetic fields, the linearity and temperature dependence, the noise level, the coupling with fast read-out electronics, with the perspective to optimize the performance to cost ratio.
- To perform the radiation test on different SiPM types using the Co-60 source of photons. Possible deterioration of the SiPM characteristics will be tested due to the effect of high doses of these radiations. A crucial point will be the definition of the best SiPM detector to be used.
- To provide the tracking system based on existing equipment.
- To participate in the prototype tests.

The primary responsibilities of the Chilean part of the collaboration (UTFSM) will be:

- To develop a dedicated front-end readout and power supply system.
- To design and develop a FPGA with software and communication between cards and computer.

The important part of the proposal is also to provide travel support, creating opportunities for the US partners (including postdoc) to participate in the hardware development, and for Italian partners to participate in the prototype assembly, commissioning of the prototype and participating in the measurements.

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