Liquid Scintillator Calorimetry for the Electron Ion Collider

Dr. Justin Frantz (Principal Investigator) and Dr. Dmitri Kotchetkov
Department of Physics and Astronomy
Edwards Accelerator Lab, Room 216
Ohio University
Athens, OH 45701
phone: 646-228-2539
email: frantz@ohio.edu

1. Objective of the Project

The objective of this project is to develop inexpensive and radiation hard technology for forward calorimetry detectors at the Electron Ion Collider (EIC). The technology will use liquid paraffin based scintillators contained in off-the-shelf commercially available cell polycarbonate panels. Criteria for this technology include safety against fire and explosion hazards, simplified production and assembly processes, low fabrication, exploitation and maintenance costs, as well as easy upgrades, replacements and disposal. During the project we will measure properties of a variety of liquid scintillators. Specific applications of the technology will be further studied and considered in follow-up R&D projects. The follow-up projects will ultimately identify what liquid scintillator forward detectors will be best to build at the EIC: electromagnetic calorimeters, hadronic calorimeters, preshower detectors, or any kind of hybrid calorimeters.

2. Calorimetry at the EIC

Calorimetry is one of the most essential components for collider detectors. It is understood that the Electron Ion Collider project needs an integrated R&D program on calorimetry. In such a program various technology options should be thoroughly investigated. Calorimetry in particle physics is a mature discipline: many calorimeters were designed, studied, built and exploited around the world. Utilizing vast experiences in the field, one can pursue a new detector design, in which performance parameters, manufacturability, metrological limits can be controlled and optimized. In-depth knowledge of a particular calorimetry technology ultimately reduces a "research" component during development of a new detector and allows concentrating more on instrumentation aspects. Also, a well-studied technology leads to timely design and construction of a new calorimeter, even under conditions of limited resources of various natures.

The integrated calorimetry R&D program for the EIC is needed, because the next generation calorimeters should be built with an optimal performance/cost ratio. And that can be achieved only if one builds few calorimeter prototypes of different geometries and designs. Then, by systematically comparing the prototypes, while evaluating costs of the future detectors, one can make a right choice what kind of calorimeters are better for the EIC. Also, studies of different technologies allow consideration of few alternative detector configurations. One configuration can serve as a main preferred choice, and others can be backup options for altered budget and construction schedule scenarios.

3. Physics Projects with Liquid Scintillators

The scintillating liquid can be made by adding fluors (scintillators) to a solvent. There are two kinds of fluors: primary and secondary. The primary fluor gets excited to a light emitting state by excited molecules of the solvent (thus it is important to keep a sufficient concentration of the primary fluor). The secondary fluor (or a wave shifter) captures the fluorescence energy of the excited primary fluor and re-emits the energy as a longer wavelength signal (to match a maximum sensitivity wavelength of the photomultiplier photocathode). Popular solvents include white-spirit, benzene, toluene, pseudocumene, isopropyl biphenyl, and other.

Liquid scintillators have been widely used in neutrino experiments, where large volumes of detecting scintillating materials are necessary. Also, liquid scintillators found applications in accelerator-based detectors designed to measure energies of electrons, photons and hadrons. One of such detectors was a lead-liquid scintillator electromagnetic calorimeter at the CERN WA-70 experiment [1] that studied large p_T direct photons. The calorimeter had a sampling structure with active layers assembled from stacks of sheets. The sheets were made from extruded teflon tubes embedded in epoxy and steel skins (for rigidity). Every teflon tube was filled with an oil-based scintillator (from Nuclear Enterprises Inc.). The tubes with liquid were read out by photomultipliers (PMTs). Every tube had 4.4 mm internal diameter, 0.4 mm wall thickness, and 2.4 m length. The calorimeter had a lateral geometry of 2 x 2 segments and a thickness of 3 segments. Every segment was made of ten layers of lead and 10 layers of teflon tubes with orthogonal readouts. The design of the WA-70 calorimeter was driven by a requirement for high π^0 and η detection efficiencies. Also, a requirement to identify hadrons, like K^0_L and neutrons, was made, so the design allowed measurement of longitudinal shower development. The sampling electromagnetic energy resolution of the calorimeter was 12.6%, while the constant term of the energy resolution was 3.2%. The calorimeter had excellent capability to reject hadrons from electrons.

Another lead-liquid scintillator calorimeter called SLIC was built for Fermilab tagged photon spectrometer [2]. The detector had a sampling structure with 60 layers of lead and scintillator. The scintillator layers were made of corrugated 5 mm thick teflon-coated aluminum sheets. The corrugations had square-wave patterns with 3.17 cm widths to form conduits for a mineral oil based liquid scintillator (with components supplied by Nuclear Enterprises, Inc. and Penreco, Inc.). The thickness of every scintillator layer was 1.27 cm. The conduits filled with scintillator were forming scintillator counters. In the assembled calorimeter the counters had 3 possible orientations, thus giving 3 coordinates for the transverse position of each shower. Absorber layers were made from 1.65 mm thick lead sheets sandwiched between 1 mm thick aluminum sheets. The mechanical design allowed longitudinal segmentation, however it was not implemented. For the same transverse position of the edges of the counters, light collection was done by a single wavebar. The calorimeter had the sampling energy resolution of 15%, while the position resolution was equal to approximately 3 mm.

Liquid scintillators were considered to be used for the forward "spaghetti" calorimeter of the SDC detector. That choice of design seemed to be appropriate for a very high radiation environment (at the SSC the annual dose would have exceeded few Gigarads at the rapidity equal to 6 units). During the R&D stage, prototype liquid fibers were designed and fabricated, with subsequent measurements of photostatistics and light attenuation lengths [3]. The prototypes were made of Pyrex borosilicate glass tubes that had internal diameters of 2 mm. Several kinds of liquid scintillators were obtained from Bicron, National Enterprises, and National Diagnostics. In each prototype the signal was readout by one photomultiplier through an optical filter. Studies of light attenuation were conducted using 50 mCu ^{90}Sr

radioactive source. The light attenuation lengths of the samples were estimated to be as large as 4-5 meters.

Liquid scintillators are very suitable to be used in radiation resistant detectors. Liquid scintillators are inherently less sensitive to radiation damage than solids. For example, a toluene-based scintillator with 2,5-diphenyloxazole (PPO) fluor starts manifesting degradation in performance after absorbing 3 Gigarads of dose from ^{60}Co source [4]. One should remember, also, that the detector can be constructed in such a way that allows circulation of liquids. Finally, if liquids and their containers are inexpensive, and design of the detector allows easy access to scintillator components, they can be just disposed and replaced with new.

4. EIC Liquid Scintillator Forward Detector

Forward calorimeters are included in the concepts of the EIC detectors. In this proposed project we would like to perform initial studies of active scintillator components that can be used to build forward sampling EIC calorimeters. The liquid scintillator technology itself is the subject of this project. Implementation of the technology and specific configurations require thorough subsequent simulation studies and prototyping, when physics requirements will be tuned, and such factors as detector design, production and maintenance costs will be taken in consideration.

The design ideas of the WA-70 and SLIC calorimeters can be adapted for the EIC. Active scintillator layers of the future EIC forward detectors can be built using commercially available cell polycarbonate panels (see Figure 1). Every cell in every panel will be filled with liquid scintillator and will be readout by two photomultipliers or by one photomultiplier (see Figure 2). The layers should be low-cost, easily maintained or/and disposed, non-hazardous. And, of course, the complete detector should have proper position and energy resolution performance parameters.

The benefit of using cell polycarbonate is in the fact that this construction material is inexpensive and has been mass-produced. The production processes simplify making individual internal conduit-cells. Thus, the detector fabrication and assembly costs should be greatly reduced, if one wants to repeat, for example, the WA-70 calorimeter. Instead of fabricating individual tube-conduits and building a sheet layer from them, just a polycarbonate panel with “already built” conduit-cells for the liquid is needed. Among many excellent exploitation properties, polycarbonate is a light-weight and very hard material.

There are several configurations of the scintillator layers that will be explored in detail in the follow-up projects. Figure 3 presents, as an example, one configuration of a scintillator layer seen from the vertex. The layer is assembled from eight identical cell polycarbonate panels to form a “wheel”. A particle can cross as many as 4 panels with this configuration, giving 4 position coordinates. The minimum number of crossed panels is 1. Figure 4 shows a configuration of the scintillator layer, seen from the vertex, as a “wall” made from just 4 identical panels. As in the case of 8 panels per layer, in the 4-panel “wall” every next panel is placed behind. So, for example, if the panel has a thickness of 1 cm, then 8-panel “wheel” has a combined thickness of 8 cm, and 4-panel “wall” has a thickness of 4 cm. Note that in these configurations, the photomultipliers are located reasonably far from the beamline.

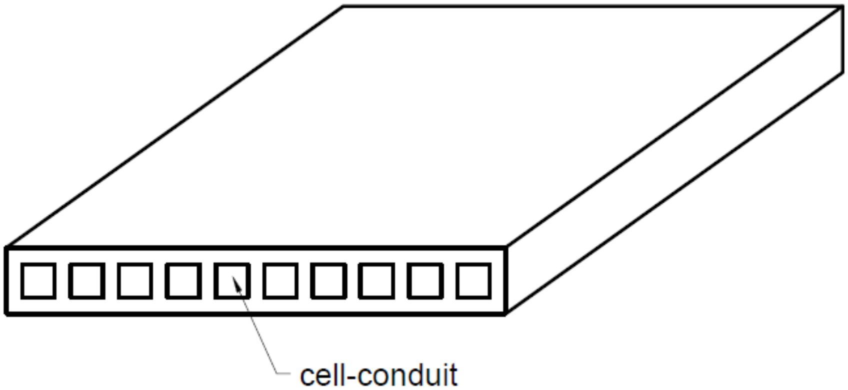

Figure 1. Cell polycarbonate panel.

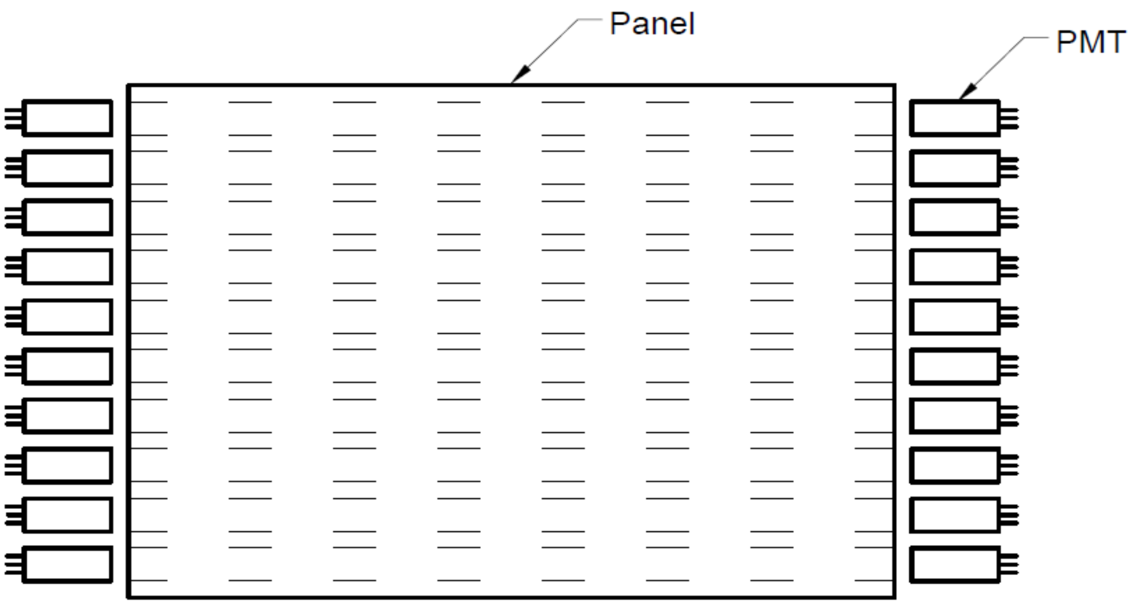

Figure 2. Panel in which every cell (shown horizontally oriented) is readout by two photomultipliers. Dash lines show contours of internal walls that separate cells.

The scintillator layer can also be assembled from non-identical panels. Figure 5 shows an example of the layer built from 2 long and 2 short panels to allow the beampipe to pass. Thin lines represent internal walls that separate cells in the panels (scale in the Figure is arbitrary). A signal from every long panel cell can be readout by 2 photomultipliers. But cells in the short panel can be read out by one PMT, placed at the panel edge which is far from the beamline. The edge of the short panel, located near the beamline, can be, for example, covered inside with reflective paint. Several layers placed next to each other with orthogonal orientations of the cells will resemble design concepts of the WA-70 and SLIC detectors.

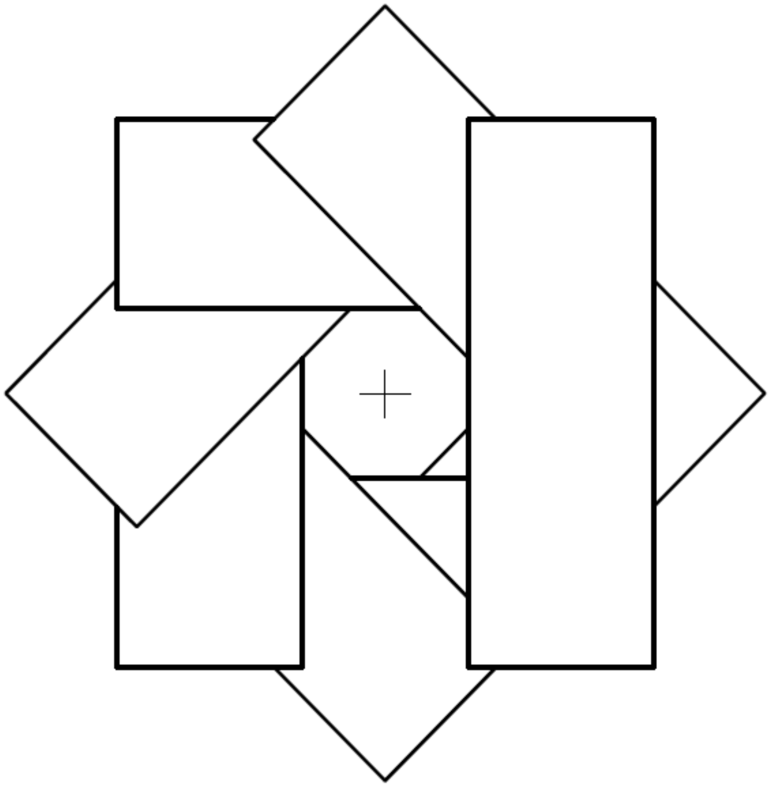

Figure 3. “Wheel” of a scintillator layer assembled from 8 identical polycarbonate panels.

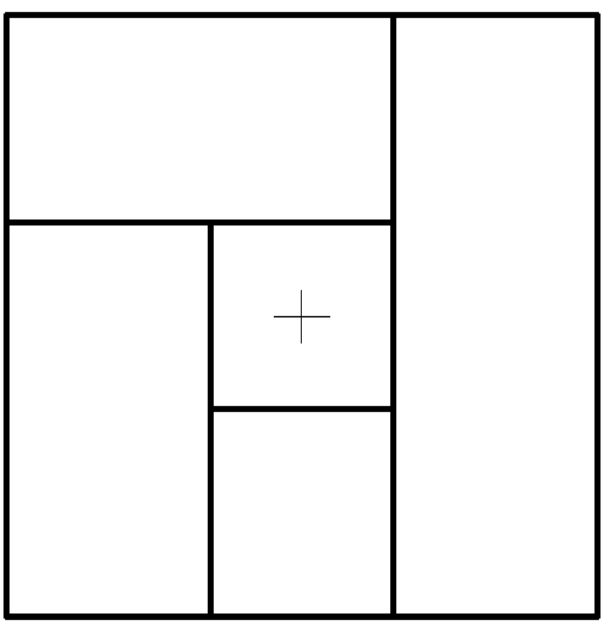

Figure 4. “Wall” of a scintillator layer assembled from 4 identical polycarbonate panels.

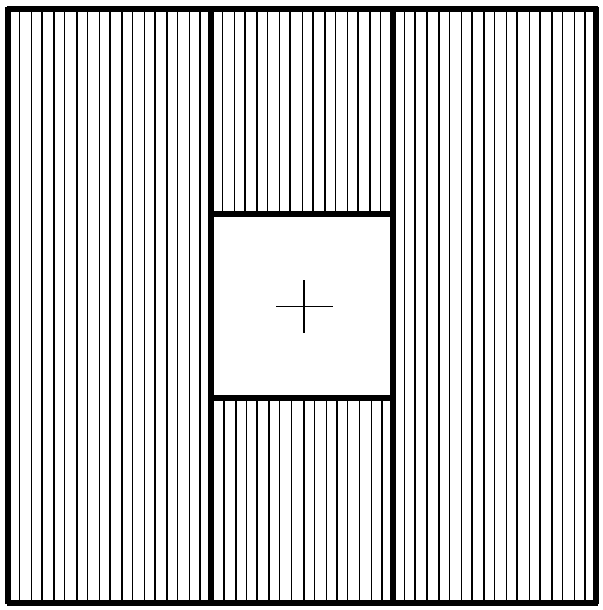

Figure 5. “Wall” of a scintillator layer assembled from 4 non-identical panels.

5. Polycarbonate

Polycarbonate sheet panels have been mass-produced in industry mostly for construction and farming needs. Different vendors offer polycarbonate panels which are 12-250 times stronger than glass. Polycarbonate panels are inexpensive, so they gain popularity where windows, walls and other building elements need to be installed. Figure 6 shows an office room with walls made from polycarbonate. Transparent and non-transparent polycarbonate panels with different colors can be manufactured. The material has a density of 1.2 kg/m^3 and a glass transition temperature of 150^{0}C. The index of refraction of transparent polycarbonate is equal to 1.58-1.59. The material is radiation hard. Radiation damage for polycarbonate and similar polymer materials manifests in modified mechanical properties; for example, the material can become brittle. Studies, conducted on radiation hardness of polycarbonate, demonstrated that the material shows no changes in the values of Brinell hardness number after absorbing a dose equal to 100 Mrad [5].

Cell polycarbonate has air gaps between panel sheets (see Figure 7). The air gaps are mechanically separated by internal walls. This leads to high rigidity and low masses of the panels. Production of cell polycarbonate requires processes which differ from the processes for monolithic polycarbonate. Also, frequently, performance parameters of monolithic polycarbonate are achieved with cell polycarbonate panels which require less amount of material. Different production processes and the lower material budget lead to lower market prices for the cell polycarbonate panels compared to the monolithic panels. One of the advantages that the cell panels have over the monolithic panels is those air gaps. Thus cell panels isolate heat better than the monolithic panels. As a result, in construction, cell polycarbonate is more popular than monolithic polycarbonate. Industry produce cell polycarbonate panels with thicknesses of 4-32 mm. The mass of 1 m^2 panel is usually equal to 1.5-3.5 kg.

Figure 6. Office with walls made from polycarbonate.

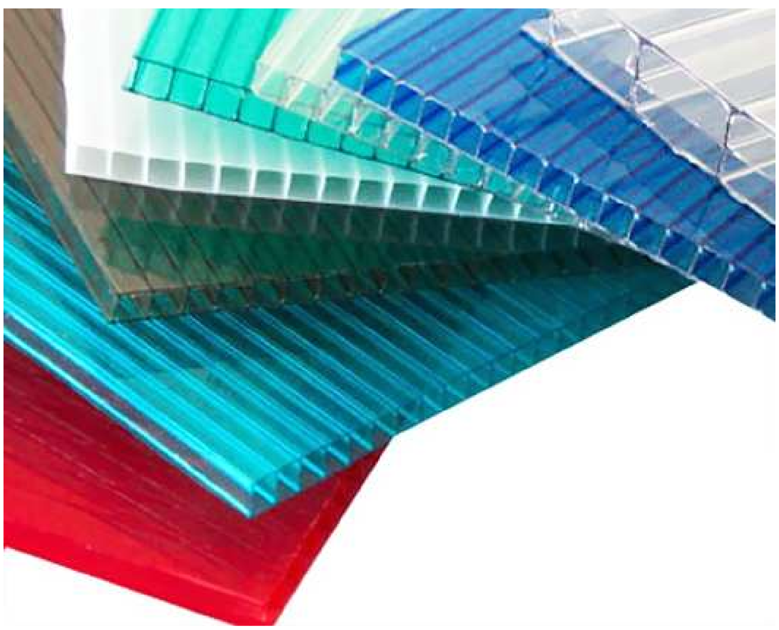

Figure 7. Cell polycarbonate.

6. Liquid Scintillator Solutions

A variety of liquid scintillator solutions for physics detectors have been developed and applied. Liquid scintillators based on toluene have been considered among best in the field. Using toluene with such primary fluors as p-terphenyl, 2,5-diaryloxazoles, or 2,5-diaryl-1,3,4-oxadiazoles guarantees a high scintillator efficiency. A mixture of p-terphenyl (4 g/l) and 1,4-bis(5-phenyl-2-oxazolyl)benzene (POPOP) (0.1 g/l) in toluene is recognized as an etalon in liquid scintillator technology. The scintillating efficiency of such a mixture is considered to be 100% (however, there are toluene-based solutions with efficiencies higher than 100%). Unfortunately, toluene-based scintillators have rather low boiling temperatures (110^{0}C) and low flash temperatures (4^{0}C), the later make these scintillators fire and explosion hazardous.

A better scintillator can be made if one adds 2,5-diphenyloxazole (PPO) or 2-phenyl-5(4-diphenyl) 1,3,4-oxazol (PBD) to ditolylmethane. Such liquid has a high scintillating efficiency (125-160%), large transparency, high boiling temperature (280^{0}C), and high flash temperature (150^{0}C). However, this scintillator has not been used widely, due to high costs and limited availability of ditolylmethane.

An inexpensive scintillator can be made by using white-spirit as a solvent and PPO (1.0 g/l) and POPOP (0.03 g/l) as primary and secondary fluors. This liquid has a scintillating efficiency equal to 43% and a rather low flash temperature of 33^{0}C.

There are, also, liquid scintillators based on vaseline oil. Up to 10% of either naphthalene or alpha-methylnaphthalene should be added to the solvent, together with PPO (5 g/l). Sometimes POPOP with 0.1 g/l concentration is added to the solution, as well. The scintillators based on vaseline oil have scintillating efficiencies of 45-55% and lower optical transparencies. That limits the scope of applications of such liquids. Purification of the oil, to improve its transparency, is an expensive process, which translates to a higher cost of the liquid.

There have been continuing efforts to develop liquid scintillators that would have high scintillating efficiencies, high optical transparencies, and be made from inexpensive and easily accessible components. A somewhat novel approach to achieve such goals is to use liquid paraffin as a solvent with added aromatic hydrocarbons and fluors. Suitable aromatic hydrocarbons include naphthalene or methylnaphthalene, or xylol, or a mixture of naphthalene and xylol. For fluors, 2-phenyl-5-(4-biphenyl)-oxazole (BPO) or 1,3,5-triphenyl-2-pyrazoline (TPP), or 2,5-diphenyloxazole (PPO) can be chosen. The components should be mixed according to the following ratio:

liquid paraffin:	79.5-94.5 %
aromatic hydrocarbon:	5-20 %
fluor:	0.4-0.6 %

Liquid paraffins have a boiling temperature of 232-334^{0}C and a flash temperature of 98^{0}C. That makes paraffin-based liquid scintillators practically safe in regard to fire and explosion.

Studies of different solutions, their luminescence spectra, transparencies and scintillating efficiencies were conducted in 1990s at the Institute for Single Crystals of the National Academy of Sciences of Ukraine [6]. Table 1 shows characteristics of liquid scintillators based on liquid paraffin with added PPO as a fluor. Note that λ_{max} refers to the wavelength of maximum luminescence. The reference liquid scintillator, which has both scintillating efficiency and transparency equal to 100%, is a toluene-based liquid with p-terphenyl (4 g/l) and POPOP (0.1 g/l). Table 2 lists properties of paraffin-based scintillators with BPO fluor. Table 3 shows results of measurements conducted with paraffin-based scintillators with TPP fluor. As references, Tables 4 and 5 show properties of scintillators based on vaseline oil and white spirit.

N	liquid paraffin	naphthalene	α-methyl-naphthalene	η-xylol	PPO	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
1	94.5 %	5 %	-	-	0.5 %	370 nm	54 %	90 %
2	89.5 %	10 %	-	-	0.5 %	365 nm	64 %	90 %
3	89.5 %	-	10 %	-	0.5 %	370 nm	66 %	90 %
4	79.5 %	-	-	20 %	0.5 %	370 nm	60 %	90 %
5	79.5 %	10 %	-	10 %	0.5 %	370 nm	70 %	90 %

Table 1. Properties of scintillators based on liquid paraffin with PPO used as a fluor.

N	liquid paraffin	naphthalene	α-methyl-naphthalene	η-xylol	BPO	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
6	94.5 %	5 %	-	-	0.5 %	390 nm	72 %	90 %
7	89.5 %	10 %	-	-	0.5 %	395 nm	90 %	90 %
8	89.5 %	-	10 %	-	0.5 %	390 nm	88 %	90 %

Table 2. Properties of scintillators based on liquid paraffin with BPO used as a fluor.

N	liquid paraffin	naphthalene	α-methyl-naphthalene	η-xylol	TPP	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
9	94.5 %	5 %	-	-	0.5 %	435 nm	52 %	92 %
10	89.5 %	10 %	-	-	0.5 %	440 nm	64 %	94 %
11	89.5 %	-	10 %	-	0.5 %	440 nm	64 %	95 %
12	89.6 %	-	10 %	-	0.4 %	440 nm	62 %	94 %
13	89.4 %	-	10 %	-	0.6 %	435 nm	64 %	93 %
14	89.7 %	-	10 %	-	0.3 %	435 nm	45 %	95 %
15	89.3 %	-	10 %	-	0.7 %	440 nm	50 %	94 %
16	79.5 %	-	-	20 %	0.5 %	440 nm	58 %	94 %
17	79.5 %	10 %	-	10 %	0.5 %	435 nm	70 %	94 %

Table 3. Properties of scintillators based on liquid paraffin with TPP used as a fluor.

N	vaseline oil	naphthalene	α-methyl-naphthalene	PPO	POPOP	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
18	89.75 %	10 %	-	0.25 %	-	390 nm	72 %	90 %
19	89.5 %	-	10 %	0.5 %	-	395 nm	90 %	90 %
20	89.75 %	10 %	-	0.25 %	0.005 %	390 nm	88 %	90 %

Table 4. Properties of some scintillators based on vaseline oil.

N	white spirit	PPO	POPOP	λ_{max}	scintillating efficiency	transparency at λ = 400 nm
21	99.1 %	0.10 %	0.03 %	415 nm	43 %	88 %

Table 5. Properties of white spirit based scintillator.

7. Project Scope

We intend to study properties of paraffin-based liquid scintillators enclosed in polycarbonate containers. In this project two prototype panels, each having 3 cells, will be designed and fabricated. Then optical properties of the scintillators, poured into the prototype panels, will be investigated. The studies will include irradiation of panels by radioactive sources and measurements of the light output and light attenuation lengths.

We will use primarily liquid scintillator solutions listed in Table 1 and Table 3, however, we would like to, also, slightly modify recipes to see effects of changing concentrations. Also, in regard to the solutions that involve PPO, we will conduct measurements not only with just PPO fluor (as listed in Table 1), but also when POPOP wavelength shifter is added. Photomultipliers, to be used in the project, will have wide spectral responses to allow measurements of signals with peak luminescences of 350-380 nm, as well as of signals with peak luminescences of 420-440 nm. We exclude BPO fluor from the studies, due to its very large price, about 6 U.S. dollars per 1 miligram.

8. Prototypes

Industry produces cell polycarbonate primarily as transparent panels which are not suitable for the project. Production of non-transparent cell polycarbonate requires modification of the processes; then fabricating two panels, each with 3 cells, by a chemical plant will be very expensive. So, we will emulate cell polycarbonate panels by making the prototypes from non-transparent monolithic sheets. Thickness of the monolithic polycarbonate sheets will be 5 mm.

One prototype will have a length of 2 m. Internal dimensions of each cell will be 1 x 1 cm^2. The second prototype will be 2 m long, as well, however, cells in that prototype will be 2 x 2 cm^2 large. The total volume of a liquid contained in all 3 cells of the first prototype will be 0.6 liters. The total volume of the liquid contained in all 3 cells of the second prototype will be 2.4 liters.

Ends of both panels will be closed by transparent polycarbonate to allow light to be read out by PMTs (see Figure 8). Photomultipliers will be coupled directly to those transparent windows. Application of optical fibers for light transfer from scintillator to the PMTs is not envisioned in this project. Special mechanisms will be designed to keep PMTs attached to the panels. Also, special covers will be used to protect PMTs from accidental environmental light.

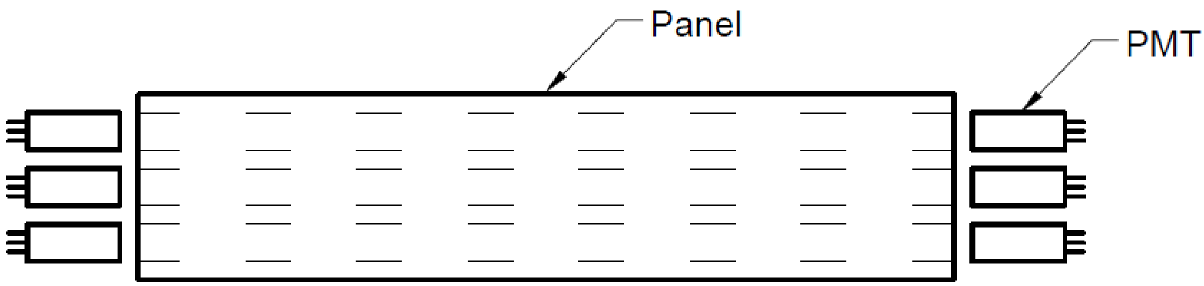

Figure 8. Prototype polycarbonate panel. The panel has 3 cells.

Measurements of the light output will be conducted with configurations using as few as just one PMT or as many as six PMTs per panel. Thus special covers will be made to make either end of the panel non-transparent.

The project assumes rather frequent refilling of the panels with liquids, so special mechanisms will be designed and made to make those refills and to keep hermeticity of the panels when they contain the liquid. The cells will be hydroisolated from each other, so we can measure the light output when just one cell is filled with scintillator, while the other two are empty, etc.

Hamamatsu photomultipliers R3878 will be employed. The R3878 PMT has a diameter of 10 mm with a photocathode active area size of 8 mm. The spectral response of this PMT is from 165 nm to 650 nm with a peak cathode sensitivity at 420 nm. The quantum efficiency of this device just slowly changes when the wavelength increases from 370 nm to 440 nm.

9. Measurements

We will follow procedures of light output and light attenuation length measurements described in literature, for example in [3]. Basically, scintillator responds to irradiation from a radioactive source. The light collected by the PMT is integrated with a pre-amplifier (Per-Amp). The output from the pre-amplifier feeds a spectroscopic amplifier (Amp), an output of which feeds an Analog-Digital Converter (ADC). The signal from the ADC is recorded and analyzed by a data-acquisition system. Figure 9 presents a case when all six PMTs are reading the signals.

Different radioactive sources can be used, such as ^{137}Cs, ^{60}Co, ^{90}Sr, and others.

Measurements of the light output will be made with changing configurations of the system. For example, the system configurations can be
- reading from all 3 cells filled with scintillator,
- reading from only one cell filled with the scintillator, while the other two cells are empty,
- reading from only one cell filled with the scintillator, while the other two cells are also filled,
- reading from the cell with two PMTs,
- reading from the cell with one PMT,
- reading from the cell with one PMT and with a reflective material placed at an opposite end of the cell,
- etc.

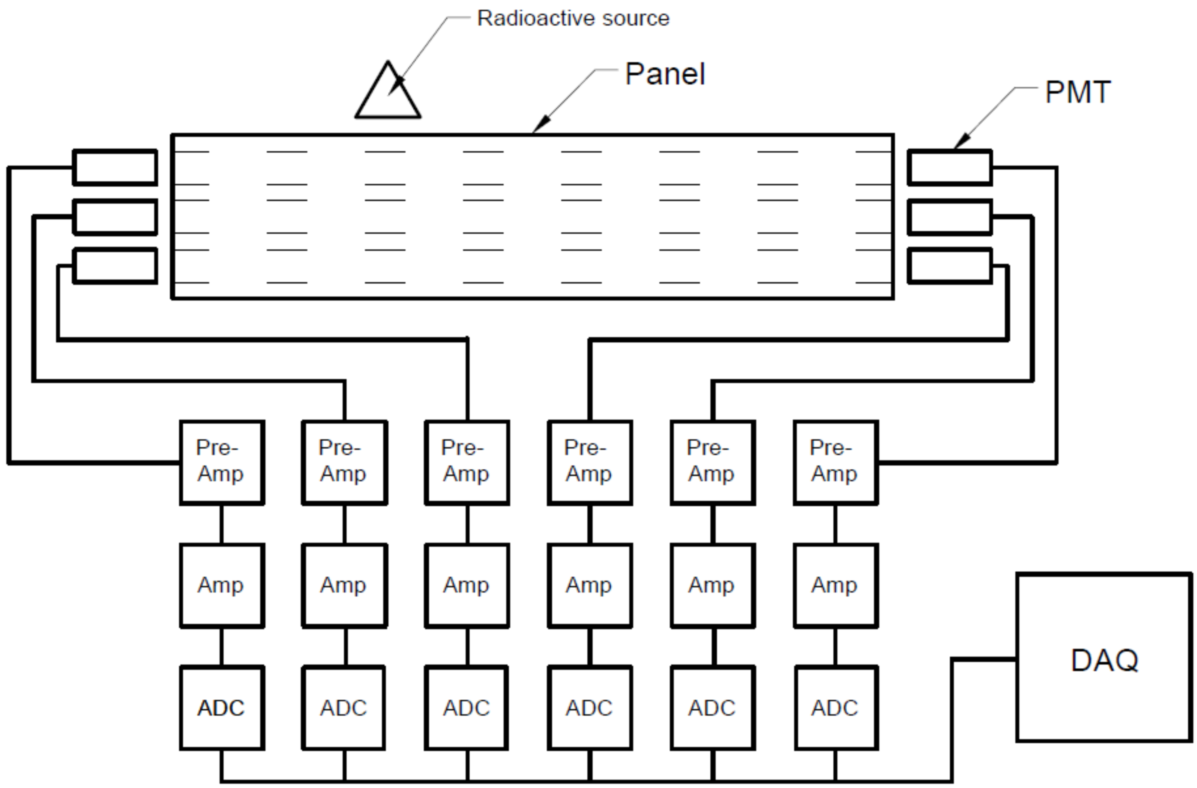

Figure 9. Setup for the measurements.

Positions of the radioactive sources in regard to the cells will be changing, too.

As it was mentioned, responses from a variety of paraffin-based solvents will be investigated. We will use PPO and TPP as primary fluors, adding sometimes POPOP as a secondary fluor to PPO.

Light attenuation lengths of the scintillators will be found by measuring the light outputs as functions of distances from the radioactive source to the PMT. Thus, the signal will be measured for different locations of the source along the cell.

10. Personnel

The Principal Investigator and one post-doc will work on this project. Two graduate students might be involved in the measurements, as part of their education activities (to be exposed to advanced detector R&D).

The Principal Investigator is a faculty at the Department of Physics and Astronomy of Ohio University and has been a member of PHENIX collaboration at RHIC for several years. He has been involved in development and maintenance of trigger and data acquisition systems, detector calibrations, software development, and physics data analysis. The PI is serving as a PHENIX Detector Council Member and Manager of Lead-Glass Electromagnetic Calorimeter (PbGl EMCal). His duties include coordination and management of various activities related to maintenance and operation of the PbGl EMCal, such as repairs, calibrations, upgrades, and data analysis.

11. Project Timeline

The total duration of the project is 1 year. During the first 4 months of the project the prototype panels will be designed and fabricated. All required equipment and chemicals will be purchased. During the following 8 months measurements of light output and attenuation lengths with different scintillator liquids will be performed, together with data analysis and results publication.

12. Manufacturer of Prototype Panels

Uniplast Ltd. Co. located in Vladimir, Russia will design, fabricate and ship both prototype polycarbonate panels. Uniplast has been one of the more successful industry vendors specializing in plastic scintillators and sampling scintillator calorimetry. Uniplast fabricated all “shish-kebab” EMCal modules for AGS E865, PHENIX, HERA-B, and LHC-b experiments. Also, the company supplied scintillator tiles for the electromagnetic calorimeters of the STAR and ALICE (U.S. part) detectors. Currently, Uniplast is supplying T2K experiment with scintillator counters. The company participated in various R&D projects, like CALICE hadron calorimetry, a lead-scintillator accordion EMCal and other.

Uniplast has qualified scientific and engineering staff, all necessary equipment and resources, and established business relations with vendors of the required materials and supplies. Fabricating the prototype panels by the company will definitely minimize the design and production costs. We anticipate that the mechanical design will be performed by Uniplast engineers, with technical coordination and necessary assistance from the PI.

13. Project Site

The project will be performed at the Department of Physics and Astronomy of Ohio University (Athens, OH). Nuclear and particle physics research efforts at the Department are organized under the Institute of Nuclear and Particle Physics (INPP). One of the major aspects of the INPP activities is the operation of the Accelerator Laboratory, which includes 4.5 MV tandem Van de Graaf accelerator. This facility has multiple beam lines and experimental areas. The accelerator is extensively used for diverse projects in nuclear physics, astrophysics, materials science, etc. The Lab has such resources as a computer farm, hardware assembly rooms, electronics testing rooms, and a stockroom.

Some of the resources of the INPP will be used in this project. Various radioactive sources are available. Also, ADC modules, amplifiers, several data-acquisition systems (mostly PC-based), as well as electronic measurement equipment items, are available for the project. The PI can get help from a fulltime electronic and computer engineer who has an expertise in scintillator detectors and data acquisition systems.

14. Requested Budget

Funds are requested for materials/chemicals and some equipment components.

<u>Materials/Chemicals:</u> **6,720 U.S. Dollars**

Liquid paraffin	25 gallons	$500
Naphthalene	7 kg	$300
α-methyl-naphthalene	2 kg	$540
PPO	0.4 kg	$470
POPOP	0.05 kg	$200
Xylol	4 liters	$110
1,3,5-triphenyl-2-pyrazoline	0.5 kg	$4,600
Materials/Chemicals Total:		$6,720

<u>Equipment:</u> **18,620 U.S. Dollars**

	Qty	
Two polycarbonate prototype panels with accessories	2	$8,500
Hamamatsu photomultiplier tube R3878	6	$5,380
Hamamatsu D-type Socket Assembly E1761-22 (includes a resistive voltage divider and connectors)	6	$1,580
Ortec 113 preamplifier	6	$2,760
Chemistry glassware and measurement accessories	N/A	$400
Equipment Total:		$18,620

(No funds are requested for amplifiers, ADCs, DAQ hardware or software components, and radioactive sources. Cost for polycarbonate prototype panels include design, fabrication and shipping from Vladimir, Russia to Athens, OH, U.S.A.)

Total Requested Budget: **25,340 U.S. Dollars**

This amount does not include indirect costs. The indirect costs are calculated on materials and equipment (if equipment costs are below $25,000). A negotiated rate of 47.5% for on-campus research at Ohio University is used to calculate indirect costs, following DOE guidelines. The rate was negotiated on September 4, 2007 with DHHS.

15. Follow-Up Projects

Obviously, a multitude of diverse follow-up projects can be conducted. From the results of this project one can estimate what minimum cell size (i.e. thickness of liquid scintillator) is sufficient to produce enough of the light output. If the project will show a potential to reduce the cell sizes, new thinner prototype panels can be fabricated and studied. Since there are no head-on PMTs with less than 10 mm diameter, using thinner than 10 mm thick panels will require application of optical fibers for light transfer from the scintillator to the PMT. Thus elaborate measurements of the readout with optical fibers will be needed. Optical fibers will be required if in the IEC calorimeter there will be no readout of every cell by one or two PMTs. That will be the case for the detector without longitudinal segmentation. Also, if one scintillator layer will be using several polycarbonate panels, then the design of the detector might consider combining signals from several cells to one PMT.

Other different liquid solutions can be studied.

After the project that involves just irradiation from radioactive sources, the prototype system(s) can be expanded to a test-bench that measures energies of cosmic muons. Also, eventually, one needs to move the prototypes to the test electron and hadron beams. Various absorbers can be explored there, and optimum sampling fractions and frequencies can be searched to reach best performance parameters. Radiation hardness studies can be performed with the test beams, as well. One should also not forget that aging studies of the system with cell polycarbonate and paraffin-based liquids scintillators will be necessary before this technology is proposed to be implemented.

And, of course, studies that are included in this project and in the follow up projects will motivate extensive simulations to find and finalize detector concept and design, in order to move the R&D work toward implementation stages.

One of potential follow-up projects can include studies of properties of scintillators based on transparent paraffin gel, as an alternative to scintillators based on liquid paraffin.

16. Bibliography

1) M. Bonesini et al., “A lead-liquid scintillator electromagnetic calorimeter for direct photon physics”, Nucl. Instr. and Meth. A261 (1987) 471.
2) V. K. Bharadwaj et al., “A large area liquid scintillation multiphoton detector”, Nucl. Instr. and Meth. 228 (1985) 283.
3) M. Gui et al., “Glass-liquid scintillating fibers for calorimetry”, Nucl. Instr. and Meth. A368 (1996) 333.
4) C. H. Mesquita et al., “Radiation Damage in Scintillator Detector Chemical Compounds: A New Approach Using PPO-Toluene Liquid Scintillator as a Model”, IEEE Trans. Nucl. Sci. 49 (2002) 1669.
5) S. N. Gladkikh et al., “Radiation Hardness of Some Polymers and Epoxy Glues”, JINR-P13-2001-275 (2001) CERN Document Server.
6) Russian Federation Patent N 2094824 C1, 1997.