FERMILAB-CONF-04-216-E
September 2004

FNAL-NICADD Extruded Scintillator

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Abstract-- **The possibility to produce a scintillator that satisfies the demands of physicists from different science areas has emerged with the installation of an extrusion line at FNAL (Fermi National Accelerator Laboratory). The extruder is the product of the fruitful collaboration between FNAL and NICADD NIU (Northern Illinois Center for Accelerator and Detector Development at Northern Illinois University). The results from light output, light attenuation length and mechanical tolerance indicate that FNAL-NICADD scintillator is of high quality. Improvements in the extrusion die will yield better scintillator profiles and decrease the time needed for initial tuning. This paper will present the characteristics of the FNAL-NICADD scintillator based on the measurements performed. They include the response to MIPs from cosmic rays for individual extruded strips and irradiation studies where extruded samples were irradiated up to 1 Mrad. We will also discuss the results achieved with a new die design. The attractive perspective of using the extruded scintillator with MRS (Metal Resistive Semiconductor) photodetector readout will also be shown.**

I. INTRODUCTION

A state-of-the-art system for the production of extruded scintillator has recently been installed and commissioned at FNAL. The facility is the result of the collaboration between FNAL and Northern Illinois University's Northern Illinois Center for Accelerator and Detector Development (NICADD).

In general, the scintillator choice for a given project is based on the compromise between light output, readout system and cost. Cast plastic scintillator may cost between $40-60 per kg. In contrast, extruded scintillator that has significantly lower price may be used if a wavelength shifting (WLS) fiber readout system is used. With this approach, the MINOS experiment was able to build two detectors that required almost 300 tons of finished extruded plastic scintillator [1]. The overall cost of the extruded plastic scintillator for MINOS was about $10 per kg. The ALICE ECAL upgrade at the LHC needs 15 tons of scintillator. Preliminary R&D studies [2] have investigated the possibility of using extruded scintillator. This technology can be the appropriate solution when a special scintillator shape is necessary. The emerging (stage 1 approved) MINERVA experiment [3] intends to use a triangle-shaped extruded scintillator as an active target. The triangular shape of the strips (approximately 2 m in length) makes the extrusion process an ideal option. The shape and the tolerance of the extrusion profile die can be optimized by means of a polymer fluid simulation process. We have made the initial attempts to develop a possible strategy for effective die design for profile extrusion. Possible applications of the extruded scintillator in new experiments will be addressed.

II. EXTRUDER

For our extruded scintillator, we use a continuous in-line compounding and extrusion process [4], [5]. The extrusion line is shown in Fig 1. This method allows us to minimize the handling of the polystyrene pellets and dopants (a blend of PPO and POPOP) that are the two major components of the extruded scintillator. A computerized system regulates the delivery of these components with high precision. During the test runs, we have been optimizing the different parameters of the extrusion process such as: correlation between speed of the puller and feed rate and temperature and pressure in the vacuum tank.

Fig. 1. Extrusion line.

With existing dies we were able to produce scintillator strips of different shapes, some with holes for a WLS fiber and some without holes for routing the top surface as needed (Fig. 2). The presence of the co-extruded hole makes

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Manuscript received September 15, 2004. This work was supported in part by the U.S. Department of Education under Grant No. P116Z010035, the Department of Energy, and the State of Illinois Higher Education Cooperation Act.

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insertion of the fiber possible and saves additional expenses. Fig. 3 displays the scintillator strip with two holes (Fig. 3b) and the strip with two WLS fibers glued and edges painted white.

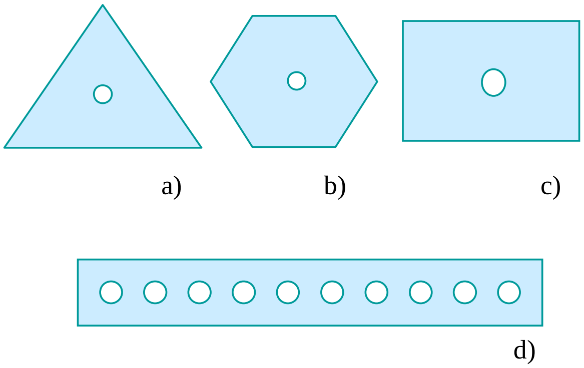

Fig. 2. Different shapes of extruded scintillator, all shapes shown have the co-extruded hole for WLS fiber insertion. a) scintillator for MINERVA, b) scintillator for Calorimeter application with pre-shower, c) shape used in R&D studies, d) scintillator strip with up to 10 holes also used in R&D.

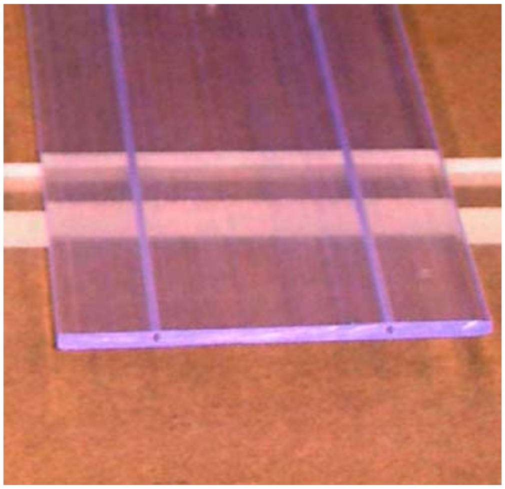

Fig. 3. Scintillator strip with two co-extruded holes.

The mechanical tolerances for the width and height of the extruded scintillator profiles can be closely controlled. Measurements performed on scintillator strips extruded at Fermilab (nominal size: 100 mm wide by 5 mm thick) yielded an average width of 101.33 ± 0.17 mm evaluated over 300 m with 50 cm interval (Fig. 4), and average thickness of 4.98± 0.03 mm evaluated over 300 m with 20 cm interval (Fig. 5).

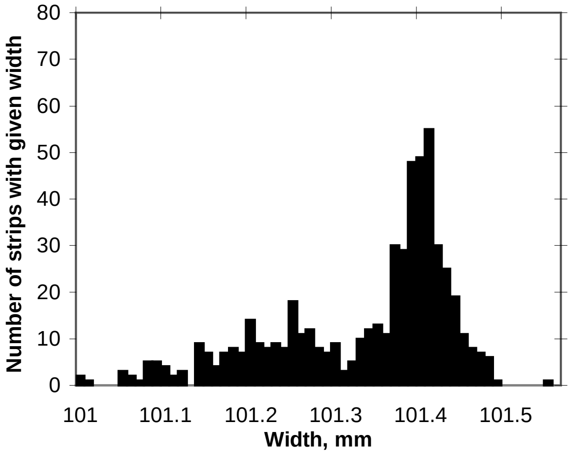

Fig. 4. Histogram of the width for extruded scintillator strips.

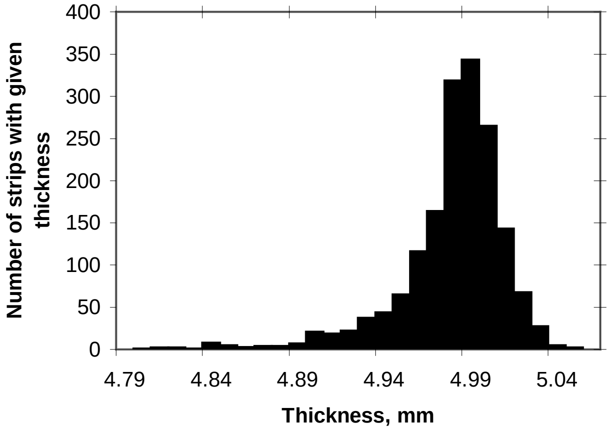

Fig. 5. Histogram of the thickness for extruded scintillator strips.

Other properties of the extruded material were studied as well, such as attenuation length, light yield, uniformity of response and radiation damage.

A. *Attenuation Length*

A sophisticated drying procedure with a nitrogen purging system allows the elimination of the humidity effects and the degradation of the plastic due to the presence of oxygen. The drying system and a vacuum station at the last stage of the extruder barrel improve the final optical quality of the scintillator plastic.

The attenuation length was measured for the following scintillators: FNAL-NICADD extruded, K2K [6] and BC404 [7]. All pieces were cut and machined to be 2x0.5x100 cm^3. All edges were polished to the same level. The co-extruded coating was removed from the K2K sample. The end furthest from the PMT was painted black. A PMT with a bialkali (K-Cs) photocathode was used, for all samples. All samples were wrapped with the same Tyvek [8] piece. A ^{137}Cs radioactive source was used.

The results of these measurements are presented in Fig. 6. In the figure, L2 is the short component of the attenuation length of each corresponding scintillator, expressed in cm.

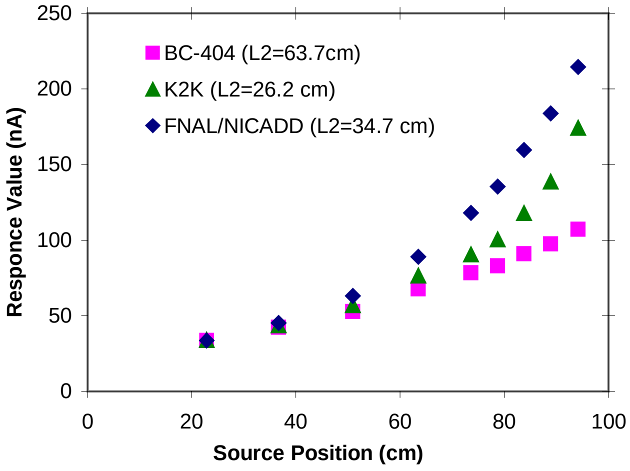

Fig. 6. Attenuation length for three different scintillators. All the responses are normalized at the 20 cm point to the value obtained from BC404 scintillator.

B. *Light Output*

Dopant optimization studies of the FNAL/NICADD extruded scintillator were undertaken to maximize the light output of the scintillator. The extruded scintillator is composed of polystyrene pellets (Dow Styron 663 W), 1% PPO and 0.03% POPOP. The light output was measured for the following scintillators: FNAL-NICADD extruded, BC408 [7] and Kuraray [9] SCSN-81. In this measurement, small pieces (2x0.5x2 cm^3) of scintillator were read out by the same PMT using a ^{106}Ru radioactive source. The results are shown in Table I. Response is normalized to 1mm thickness. The results are not corrected for spectral differences in the light emission and PMT response.

TABLE I
SCINTILLATOR RESPONSE

Type	Response (arbitrary units)
FNAL-NICADD	2.0±0.2
BC408	2.7±0.2
KURARAY SCSN-81	2.0±0.2

The extruded scintillator light output was also measured on 5mm thick samples (10x0.5x100 cm^3 strips). A 1.2 mm outer diameter KURARAY Y-11 WLS fiber was inserted in the hole. A Metal-Resistor-Semiconductor (MRS) [10] silicon sensor with 1 mm^2 photosensitive area was used for the readout. We measured ~17 photo electrons (PE) with this sensor that has quantum efficiency at 500nm of ~25% [10].

Table II summarizes the results of measurements done using the 5mm thick extruded scintillator and MRS sensor with KURARAY Y-11 WLS fibers of different diameter.

TABLE II
FIBER THICKNESS AND RESPONSE

Fiber diameter (mm)	Scintillator type and thickness	Response (PE)
1.0	Extruded[1],5mm	14.5
1.2	Extruded[1], 5mm	17
1.5	Extruded[1], 5mm	20.5
1.2	Extruded[2], 10mm	22.1

C. *Uniformity of Response*

Uniformity of the response of the extruded scintillator was measured across the 10x0.5x100 cm^3 strip and a hexagonal cell, with area of 9cm^2 and 5mm thick. The non-uniformity of response across a scintillator strip was measured and yielded a value of ~4%. The result of a similar non-uniformity scan for the hexagonal cell is <3%.

The results of these measurements are presented in Fig. 7 for the scan across the scintillating strip and in Fig. 8 for the scan across the hexagonal cell.

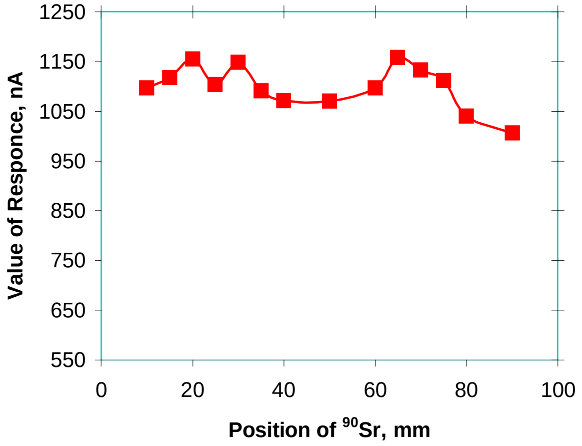

Fig. 7. Non-uniformity of response across the scintillator strip with two holes.

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[1] FNAL-NICADD extruded scintillator

[2] MINOS extruded scintillator

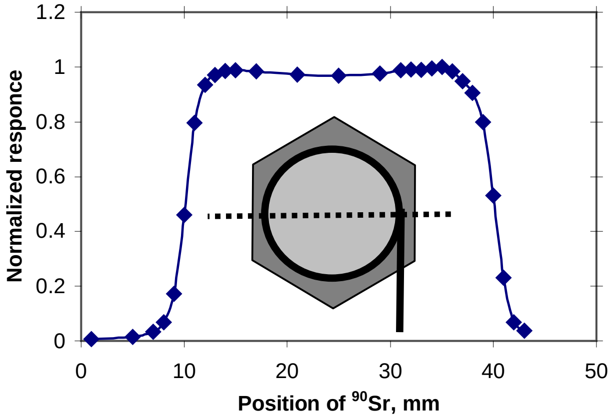

Fig. 8. Non-uniformity of response across the hexagonal cell. Response is normalized to the maximum value. The schematics of cell indicates the direction of scan.

D. Radiation Damage

Several samples of the extruded FNAL-NICADD scintillator were irradiated to 0.5 and 1 Mrad in air utilizing a ^{60}Co gamma source with a dose rate of 0.8 Mrad per hour. Only minor degradation effects in light yield are observed, similar to the value observed in cast scintillator. Pulse height (PH) measurements were performed using a ^{207}Bi radioactive source on scintillator discs (2 cm diameter and 1 cm thick) before and 85 days after the irradiation. The results are shown in Table III. PH is shown in arbitrary units.

In addition, the transmittance of the scintillator was measured, both before and after the irradiation (see Fig. 9). As with the light yield, no significant changes were observed.

TABLE III
PULSE HEIGHT BEFORE AND AFTER IRRADIATION

Dose (Mrad)	Before Irradiation	After Irradiation	Light yield loss (%)
0.5	266±9	264±8	none
1	273±6	261±7	~5

III. CONCLUSIONS

The first R&D runs on the new extrusion line at FNAL have shown the attractiveness of the FNAL-NICADD scintillator for different applications in Nuclear and High Energy Physics. The mechanical tolerances are ±0.6% for thickness and ±0.16% for width. The scintillator response, or Light Yield (LY), is within 66% of BC408 and is equal to Kuraray SCSN-81. The LY non-uniformity is <3% for the small hexagonal cell and ~4% for the long strips. The radiation damage tests yield values for the LY degradation of <5% for 1 Mrad of gamma radiation in air and at high dose rate.

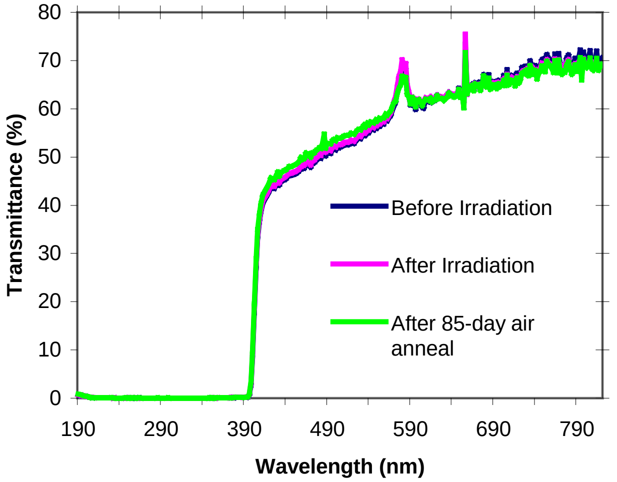

Fig. 9. Transmittance of the extruded scintillator before, after and 85 days after irradiation.

IV. ACKNOWLEDGMENT

We thank Brian Wood (UIC) and Elena Baldina (FNAL) for their valuable help with measurements.

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