FERMILAB-CONF-22-942-PPD

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Special Issue
Selected Papers from the 19th International Conference on Calorimetry in Particle Physics (CALOR 2022)

Edited by
Prof. Dr. Fabrizio Salvatore, Prof. Dr. Alessandro Cerri, Prof. Antonella De Santo and Prof. Iacopo Vivarelli

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https://doi.org/10.3390/instruments6040049 *instruments*

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Preliminary Results from ADRIANO2 Test Beams

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Abstract: A novel high-granularity, dual-readout calorimetric technique (ADRIANO2) is under development as part of the research program of T1604 Collaboration. (Talk Presented at the 19th International Conference on Calorimetry in Particle Physics (CALOR 2022), University of Sussex, Sussex, UK, 16–20 May 2022). The building block of such a calorimeter consists of a pair of optically isolated, small size tiles made of scintillating plastic and lead glass. The prompt Čerenkov light from the glass can be exploited to perform high resolution timing measurements, while the high granularity provides good resolution of the spatial components of the shower. Dual-readout compensation and particle flow techniques can be applied simultaneously to the scintillation and to the Čerenkov section, providing excellent energy resolution as well as PID particle identification. These characteristics make ADRIANO2 a 6-D detector, suited for High Energy as well as High Intensity experiments. A report on the status of the ADRIANO2 project, preliminary measurements of light yield, and current and future R&D plans by T1604 Collaboration are discussed.

Keywords: calorimetry; dual-readout; ADRIANO2

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Citation: Gerald C. Blazey; Blazey, G.; Dychkant, A.; Elam, J.; Figora, M.; Fletcher, T.; Francis, K.; Liu, A.; Los, S.; Le Mathieu, C.; et al. Preliminary Results from ADRIANO2 Test Beams. *Instruments* **2022**, *6*, 49. https://doi.org/10.3390/instruments6040049

Academic Editors: Fabrizio Salvatore, Alessandro Cerri, Antonella De Santo and Iacopo Vivarelli

Received: 13 August 2022
Accepted: 5 September 2022
Published: 22 September 2022

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1. Introduction

The physics program at future high intensity and high energy experiments encompasses a very large number of processes, involving final states, in many cases, with complicated topologies and overlapping showers. In such an environment, calorimeters will play an important role, especially at energies above 100 GeV, as their energy resolution scales, in most cases, is $1/\sqrt{E}$. An intensive detector *R&D* and Monte Carlo simulation activity is already in progress within the lepton and hadron colliders communities [1]. When used in a lower-energy environment, a dual-readout calorimeter has excellent Particle IDentification (PID) capabilities, since the two independent information, obtained from each readout, provide a much better separation between particle species than a conventional, single-readout calorimeter. Consequently, a dual-readout calorimeter also has several applications for high-intensity experiments, where the final states typically have simpler topologies. In those cases, the knowledge of the particle ID is, often, more desirable than an excellent energy resolution.

The general consensus within the lepton collider community is that the jet energy resolution needed to successfully distinguish the W from the Z signal at energy ($E > 500$ GeV, scales as $\sigma(E)/E \approx 30\%/\sqrt{E}$) or better. Such a resolution is unprecedented for conventional, single-readout hadronic calorimeters, and it has been reached in the past only by compensating calorimeters with "with a large fraction of active material [2]. We note,

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

incidentally, that a similar compensation effect can also be obtained with a small sampling fraction[3], and that the best resolution achieved is close to 30%/sqrt(E) [4]. The large volume needed to contain the showers in that class of calorimeters would make them an impractical choice for experiments with colliding beams. Furthermore, the resolution of conventional, single-readout calorimeters is limited by the fluctuations in the electromagnetic (*EM*) content of the hadronic shower and by the unequal response of such devices to the *EM* and hadronic components of the shower itself ($e/h \neq 1$) [5].

In recent years, dual-readout calorimetry [6] has been introduced as an alternative technique to cope with those effects. The dual-readout technique relies on the concept of event-by-event energy compensation by measuring, independently, the *EM* and hadronic component of each shower. As already noted, the two measurements can also be exploited to identify the particle that initiated the shower.

Dual read-out calorimetry falls under two categories: sampling and integrally active. Sampling dual-readout techniques are currently investigated by several collaborations (cfr., for example, [6–8]). While advantageous from the costing point of view, the sampling approach introduces in the energy measurement process two extra sources of energy fluctuations: (a) Poisson fluctuations in the Čerenkov signal, induced by the low photo-electron statistics, and (b) sampling fluctuations, associated to the use of a totally passive absorber. Such fluctuations not only degrade the energy measurement, but they also have detrimental consequences on particle identification. While available space and cost constraints would justify the adoption of a sampling dual-readout calorimeter in High Energy experiments, a preferred choice for High Intensity experiments would be an integrally active dual-readout technique. In such cases, in fact, the experiments are typically performed at a lower energy, therefore requiring smaller volumes to contain the particles. The showers produced have lower occupancy than those generated in High Energy experiments, and jets are rarely observed, justifying, in that case, the adoption of integrally active calorimeters, where the absorber is also active and it participates in the compensation mechanism by producing a Čerenkov signal.

The precursor of the integrally active dual readout calorimetry is the ADRIANO technique [9,10]. The central idea of ADRIANO was to mix layers of scintillator and Čerenkov radiators to independently measure the hadronic and the electromagnetic components of the energy deposited in the calorimeter. Several ADRIANO prototypes have been built and tested over the years in order to determine the relevant detector parameters and to optimize the performance in either High Energy or High Intensity applications. The baseline structure of a Čerenkov module in ADRIANO consists of long lead glass plates read out with wavelength-shifting (WLS) fibers, the latter optically coupled to the plates. The number of such fibers can be varied, depending on the application and on the desired performance. Different scintillating modules were also built using different techniques, consisting, for example, of long plates of scintillating plastics or sparsified scintillating fibers, embedded in the volume of the Čerenkov radiator, and optically decoupled from the latter.

A picture of three ADRIANO prototypes during the assembly phase is shown in Figure 1.

The R&D on ADRIANO spanned almost a decade, and several test beams were performed to characterize the technique and optimize the performance of the detector. The results [10] have indicated that the light yield (LY) of several prototypes met or exceeded the requirements set for several High Energy and High Intensity experiments. The development of ADRIANO has set the stage for the new generation of integrally active, dual-readout techniques: ADRIANO2, where the advantages of dual-readout compensation and a highly granular layout are integrated. The ADRIANO2 technique will be discussed in detail in the rest of this article.

Figure 1. *Three 105 cm long ADRIANO prototypes during the assembly phase at Fermilab's Thin Film Facility.*

2. Description of *ADRIANO*2 Techniques

All ADRIANO prototypes built within the T1015 project demonstrated consistently high light yield and good uniformity. While the non-segmented, log-style ADRIANO modules offer a low-cost solution for certain calorimetric applications, where a small number of readout channels is desired, they lack the high granularity and fast timing characteristics that are becoming increasingly important in today's experiments. This limitation is intrinsic to the chosen layout and to the inherent slowness of WLS's fibers, a characteristic that spoils the prompt aspect of Cerenkov light. The ADRIANO2 technique aims at resolving the above limitations by choosing small tiles of a plastic scintillator and of a Čerenkov radiator as building blocks of the calorimeter. The light generated in each tile would be individually read out with one or more silicon photomultipliers (SiPM) directly coupled to the tile (on-tile-SiPM). This relatively novel approach maintains the benefits of dual readout calorimetry, while opening up the possibility of applying Particle Flow Analysis (PFA) algorithms [11] to track the showers as they develop in the calorimeter, and to associate them with tracks upstream and muons downstream. Furthermore, since the Čerenkov signal is prompt, it can be exploited to accurately determine the time of passage of a charged particle in each tile for Time-of-Flight (ToF) measurements or for fast-triggering the data acquisition. Thus, three distinct measurements of the energy deposition in every scintillator-radiator tile pair can be made: the amplitude of the charge deposited, the component of the charge that is from electrons, and its precise time of arrival. The key ingredient of ADRIANO2 is the collection of the Čerenkov light produced inside small lead glass tiles, using fast SiPMs directly coupled to the glass and a fast electronics readout. Multiple tiles are sandwiched to build a calorimeter tower or a module. Typical dimensions of a tile are several cm for the side and about 1 cm for the thickness. The SiPM's and the front end electronics (FEE) are mounted on a printed circuit board (PCB) facing the tile. The latter might eventually have one or more dimples to accommodate the SiPM. A similar technique has been extensively developed at NIU [12,13] for the plastic tiles employed for the HGCAL of CMS. If several SiPM are used for reading each tile, a weighted mean algorithm can be applied to determine the position of the impinging particle. This is possible since the lead glass is a highly dispersive optical medium and the, mostly-blue Čerenkov light has a typical light path inside the tile of about 1 cm. Therefore, the amount of light reaching each sensor is a direct function of the distance it travels before being collected. This curbs the time jitter of the detector due to the small size of the tile, since only the photons traveling directly toward the sensor have a good probability of being collected, while those that follow a path with multiple bounces are, typically, absorbed. This effect portends to a very good timing resolution for ADRIANO2.

The R&D ongoing in T1604 Collaboration aims at studying the performance (light yield and timing resolution) of the glass tiles with regards to several fabrication parameters. The latter are: dimensions, surface finish, type of coating, and the eventual presence of a dimple to accommodate the SiPM. All tiles are considered have a footprint of 30×30 mm^2, matching the size of the scintillating tiles employed for the HGCAL of CMS. Thicknesses of 10 mm, 20 mm, and 30 mm were used for the prototypes. The tiles were cut to size from larger blocks of Schott SF57HTUltra, and either left ground or polished with a commercial procedure (Cat-i-glass, Elgin, IL 60177, USA). A cylindrical dimple is imparted to some of the tiles with a small-grit, diamond grinder. The dimple was subsequently polished with a water-based diamond paste. A picture of several dimpled tiles is shown in Figure 2 with blue masking fluid protecting the dimple before the coating process.

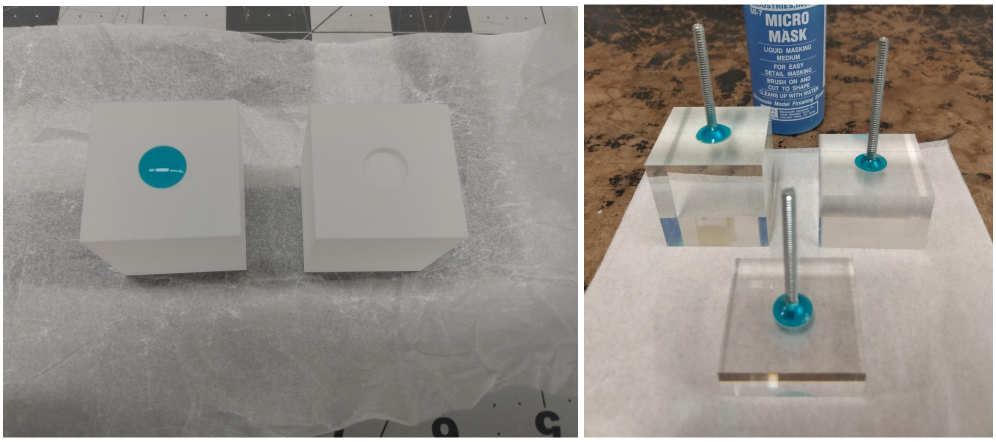

Figure 2. Ground (**left**) and polished (**right**) SF57HHT glass tiles of various dimensions.

Finally, the tiles were either wrapped or coated to suppress any leakage of the light generated internally by the particles above the Cerenkov threshold. Two diffuse wrapping (Teflon and Tyvek), two reflective wrappings (Esr2000 and aluminized Mylar), one diffuse coating (AvianB, BaSO4-based paint), and six reflective coatings (Al sputtering, Al paint, Ag sputtering, Ag paint, Mo-ALD, W-ALD) were considered. The Al sputtering was performed independently in the Chemistry Dept. of NIU and at Euclide Techlabs [14]. All atomic layer deposition (ALD) coating was conducted at the Argonne National Lab (IL).

A picture of several coated and wrapped tiles is shown in Figure 3. The area facing the SiPM is masked with Kevlar tape or masking fluid to allow the light to reach the photo-sensor.

Figure 3. Sample of coated and wrapped ADRIANO2 glass tiles.

3. ADRIANO2 Readout System

The Front End Electronic (FEE) board, holding the photon sensor and the readout electronics, consists of a small board originally designed for the ORKA project, and subsequently modified for applications where fast timing is required [15]. The active component is a GALI-S66+ amplifier with a 12× gain and a bandwidth of 0.05–1500 MHz. An optional Peltier element could be accommodated. The board has multiple pads for hosting a variety of SiPM's, spanning several Hamamatsu families and sensor dimensions. One special version was designed at Fermilab, in which the central sensor was replaced by four peripheral sensors, actively ganged into one amplifier. A picture of a single-sensor and of a quadruple-sensor FEE boards are shown in Figure 4. Two species of Hamamatsu SiPM's were used for the measurements: the S14160-6050 and the older S13360-6050.

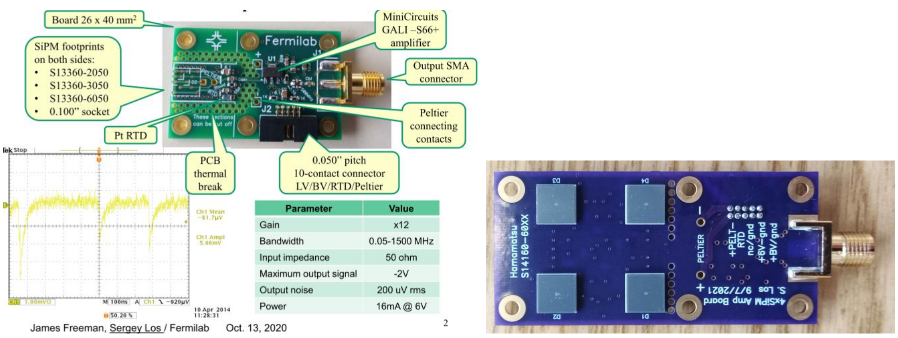

Figure 4. Single-sensor (**left**) and quadruple-sensor (**right**) FEE boards for ADRIANO2 light capture.

The FEE board is complemented by a 4-channel control board [15], to which up to four SIPM Amp boards can be connected. The control board supplies a common low voltage power for the amplifiers. All channels feature individually regulated bias and Peltier power voltages, along with a Pt10K RTD readout.

Two different DAQ systems were employed to acquire the signals from the FEE boards. A 32-ch Sampic Time Digitizer [16] was used for timing measurements, while a 16-ch Wavecatcher [17] system was used to digitize the waveforms and extract light yield information. The calibration of each board was performed by self triggering the acquisition and by fitting the distribution with multiple Gaussian curves.

4. Preliminary Results and Discussion

The current R&D focuses mainly on the lead-glass tiles, since the response of plastic tiles has been extensively studied in the past. The ADRIANO2 tiles with the same coating and surface finish were assembled into triplets consisting of 10 mm, 20 mm, and 30 mm tiles. Up to seven such triplets were positioned in a dark box and exposed to a beam of 120 GeV protons at the Fermilab test Beam facility (FTBF). A picture of the test beam setup is shown in Figure 5. Several test beams were necessary to test all combinations of surface finish and coating/wrapping. The layout chosen has the advantage that up to three tiles of the same species (belonging to the same triplet) can be used in coincidence to trigger the DAQ. Therefore, one could perform, at the same time, measurements of light yield, timing, and efficiency. A small rod of quartz with dimensions $3 \times 3 \times 6$ mm^3 readout by a Hamamatsu 4160-4050 SiPM was also used as an external trigger and as a beam position monitor. The rod was mounted on a remotely controlled x-y stage and used to scan the tile response with regards to the position of the impinging proton. All triplets were equipped with single-sensor FEE boards. One triplet, consisting of ground-surface tiles coated with Avian-B paint, was equipped with a set of 4-sensor boards.

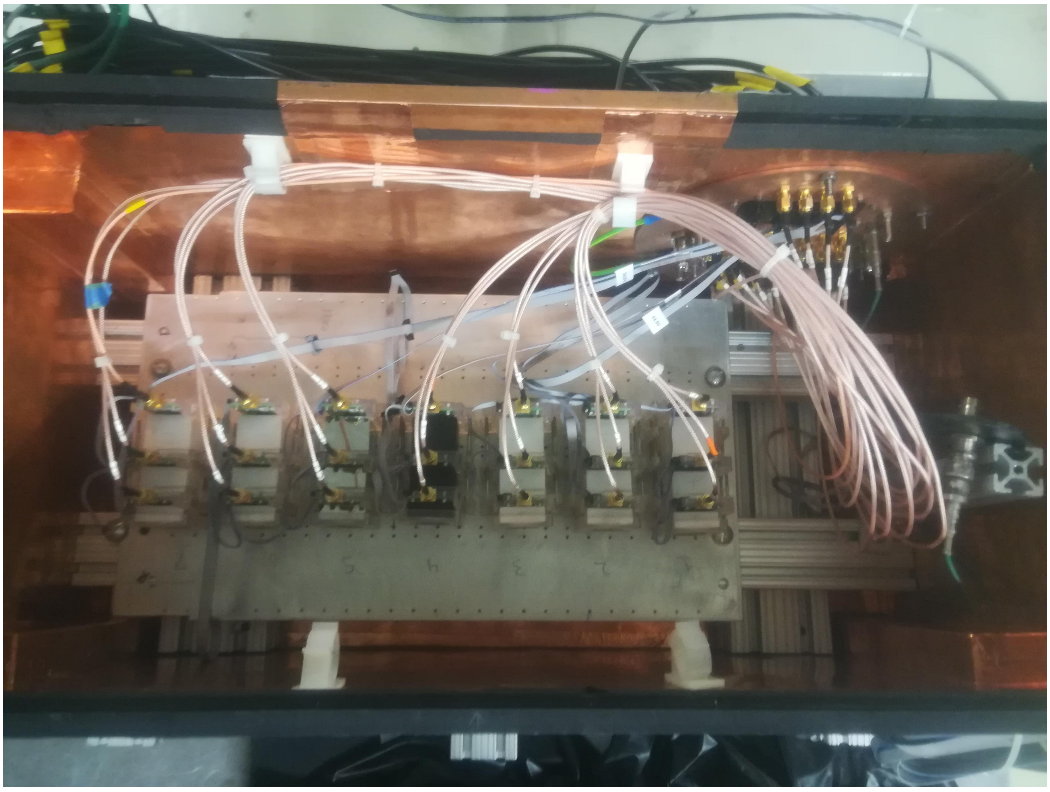

Figure 5. Setup of a test beam at Fermilab's *FTBF* of seven triplets of *ADRIANO*2 tiles.

The average light yield (photoelectron/mip), measured at the center of the tile for twenty-one triplets is summarized in Figure 6. The x-axis indicates the thickness of the tile.

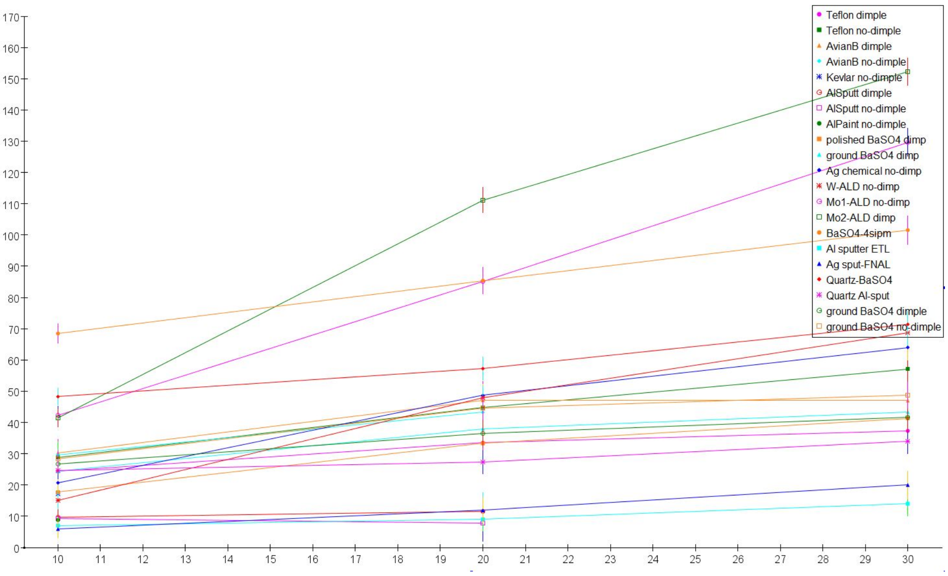

Figure 6. Light yield for 21 groups of tiles corresponding to several surface finish and coatings/wrappings.

4.1. Light Yield Measurements

The average energy deposited by a MIP particle in SF57HHT glass is ∼9 MeV. The LY shows a linear dependence from the tile thickness, although the rate of change is lower than the unity. The same behavior was also reported for the plastic tiles of CMS's HGCAL [18], so it was not unexpected. The tiles instrumented with the 4-sensor FEE board consistently have a larger LY compared to all others, thanks to a 4× larger sensitive area. However, the improvement in the LY is only a factor ∼2.3× compared to tiles with analogous surface finish and coatings, but instrumented with single-sensor FEE boards. We also observe that the presence of a dimple does not appreciably change the LY. All tiles with mirror coating have a LY consistently lower than the tiles with diffuse coating. The only exception was observed in the two triplets coated with an ALD thin-film of Mo (differing by the thickness of the Mo film: 50 nm vs. 80 nm), which shows a LY unusually large, and a rate of increase in LY vs. tile thickness approximately two times as large as all other tiles. We are further investigating this effect, to make sure that it does not have instrumental origins. The plot in Figure 6 also shows the light yield for two tile triplets made of JGS1 glass. The measurements for those will be discussed in an upcoming article.

The Esr2000 and Al-Mylar wrapping exhibit a strong fluorescence component concomitant with the Čerenkov signal. This can be observed in the left plot of Figure 7, showing the emission spectrum of both films at 440 nm, measured with a TI QuantaMaster4/2006SE spectrofluorimeter. The right picture in Figure 7 shows a typical waveform obtained from a tile wrapped in Esr2000 when exposed to a 120 GeV proton beam, along with the waveform obtained from mirror coated tiles. For these measurements, the sampling rate of the Sampic was set at 6.4 Gsa/s (a S14160-6050 sensor was used for all waveforms). The risetime of the Esr2000 is ∼6 ns, about five time larger than that measured for the other tiles, confirming that the fluorescence component is a non-negligible fraction of the total light collected by the sensor. A similar behavior was already observed by other experimenters [19]. The longer risetime makes these kind of films unsuitable for fast timing measurements. Therefore, the corresponding tiles were dropped from further measurements.

Analysis of the efficiency measurements with regards to the position of the beam are still in progress. Results will appear in an upcoming publication.

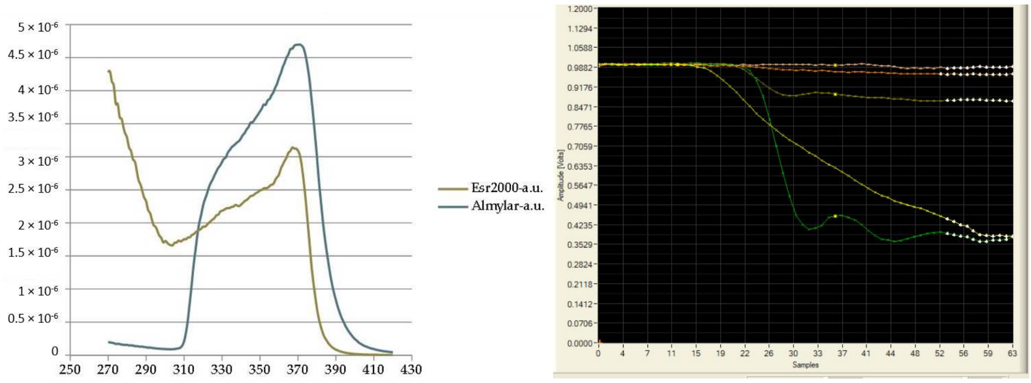

Figure 7. *A 440 nm emission spectrum (**left**) and digitized waveform (**right**) of Esr2000 and Al-Mylar films.* The sampling rate of the Sampic was set to 6.4 Gsa/s.

4.2. Timing Measurements

The analysis of the timing measurements obtained with the Sampic are still in progress and will be published in an upcoming article. Nonetheless, the behavior across the tiles families appears to be quite consistent. All mirror coated tiles have a consistently fast risetime (∼1 ns with the S14160-6050 sensor and ∼3 ns with the S13660-6050 sensor). Timing resolution in the range ∼50–100 ps have been estimated when a constant fraction discrimination is applied (via software). On the other hand, all tiles coated or wrapped with diffuse materials exhibit a long risetime (∼8 ns) and, consequently, a much worse timing resolution in the range of ∼150–250 ps. The effect is till being investigated, although it suggests that the photons are bouncing several times off the diffuse coating before eventually reaching the light sensor. The tiles instrumented with four sensors have a time resolution of ∼80 ps, regardless of the fact that they are coated with the Avain-B white paint. Further tests should help in clarifying the above behavior.

5. Conclusions

Several ADRIANO2 tiles, with thicknesses ranging from 10 mm to 30 mm, have been fabricated, using different surface finishes and coatings. Preliminary results from several test beams at FTBF have been reported. The light yield for nineteen groups of three tiles with the same fabrication parameters has been measured using a 120 GeV proton beam. Studies for the determination of the timing resolution of ADRIANO2 tiles are still in progress. Our goal is to identify a fabrication technique such that the timing measurement for each tile has a resolution of 80 ps (or better) when traversed by a minimum ionizing particle. Furthermore, the light yield must be consistent with an EM energy resolution of $\sigma(E)/E \approx 2\%/\sqrt{E}$ or better (stochastic fluctuations only). Five of the groups tested exhibit a light yield consistent with that goal. Preliminary analysis of the tiles' timing response suggests that three groups also possess the desired timing properties. T1604 collaboration will address these issues in the future and it will eventually exploit new coatings with improved performance for the Čerenkov light.

Author Contributions: These authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Department of Energy and Environment grant number G1A62765.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank Evgueni Nesterov (Chem. Dept.—NIU) for their help with the optical measurements and for providing the infrastructure for the Al sputtering of the tiles. We also thank Euclide Techlabs for assisting with the Al sputtering of the tiles. The work was supported by the grant #G1A62765 funded by the U.S. Department of Energy, Office of Science and by the Fermilab's Detector R&D program.

Conflicts of Interest: The authors declare no conflict of interest.

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