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Status of Dual-readout R&D for a linear collider in T1015 Collaboration

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Abstract. The hadronic energy resolution required for an hadronic operating at lepton collider is at the limits or even exceeds that obtained with traditional techniques. Furthermore, it is a well established fact that the presence of an electromagnetic section in front of an hadron calorimeter, as occurs in the layouts of the majority of detectors operating at a collider, would deteriorate the hadronic energy resolution of the device. The novel *ADRIANO* technology (*A Dual-readout Integrally Active Non-segmented Option*), currently under development at Fermilab, overcomes the above limitations by complementing an integrally active calorimeter with the dual-readout technique. Detailed Monte Carlo studies indicate that the energy resolution is in the $25\%/\sqrt{E}$ - $38\%/\sqrt{E}$ interval with a linear response of the detector up to an energy of 200 GeV. A baseline configuration is chosen with an estimated energy resolution of $\sigma(E)/E \approx 30\%/\sqrt{E}$. Several prototypes have been built by *T1015* Collaboration at Fermilab, to explore the effect of modifications of the layout from the baseline configuration. Preliminary results from several test beams at the *Fermilab Test Beam Facility* (FTBF) of $\sim 1\lambda_I$ prototypes are presented. Future prospects with ultra-heavy glass are, also, summarized.

1. Introduction

The physics program at future lepton and hadron colliders encompasses a very large number of processes involving final states with multi-jets events. In such an environment, calorimeters will play an important role at energies above 100 GeV, as their energy resolution scales, in most cases, as $1/\sqrt{E}$. An intensive detector *R&D* and Monte Carlo simulation activity is already in progress within the lepton colliders communities[2].

The general consensus within the lepton collider community is that the jet energy resolution needed to successfully distinguish the W from the Z signal in a high energy ($E_{cm} > 500\text{GeV}$) is $\sigma(E)/E \approx 30\%/\sqrt{E}$ or better. Such a resolution is unprecedented for conventional hadronic calorimeters and it has been reached in the past only by massive compensating calorimeters with very small volume ratio between passive and active materials[3]. Unfortunately the average density of detectors with such properties is relatively low. Consequently, the volume needed to contain the showers would be so large to make their use impractical in 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 ($e/h \neq 1$)[4].

In recent years, dual-readout calorimetry[7] has been introduced as an alternative technique in order to cope with those effects. The dual-readout technique relies on measuring event-by-event the *EM* fraction of the shower and is based on the simultaneous acquisition of signals generated by independent shower production mechanisms, thus providing complementary information on the composition of the hadronic shower.

Dual read-out calorimetry falls under two broad categories: sampling and integrally active. Sampling dual-readout techniques are currently investigated by the *DREAM*[7] Collaboration. Extensive *R&D* conducted in recent years by *DREAM* has confirmed the several advantages of the dual-readout technique. However the sampling approach introduces two new important sources of energy fluctuations: Poisson fluctuations in the Čerenkov signal, induced by the low photo-electron statistics and sampling fluctuations, generated by the fact that the absorber is totally passive and the signals are generated only in a small fraction of the volume. Those fluctuations do not only impair the energy resolution of hadronic particles and jets, but have also detrimental consequences on the detection quality of photons and electrons. The detection of *EM* particles in high energy jets is similarly affected. An obvious solution to the latter problem would be to design a detector with two distinguished regions: a front *EM* section and a rear hadronic section. However, nowadays it is well understood that such a configuration is sub-optimal in terms of energy measurement of hadronic particles due to the extra fluctuations introduced by the development of the shower across two different sections which, in most cases, consist of media with very different properties [4].

Integrally active dual-readout techniques, on the other hand, are mostly free of the above limitations since the the absorber is also active and it participates in the compensation mechanism with the production of the Čerenkov signal. Test beams and extensive simulations indicate that these techniques provide the energy resolution required by the future lepton colliders and are capable of operate at the same time as hadronic and *EM* detectors, with no need for separate devices.

In this article we will give an update on the status of the Dual-Readout, Integrally Active and Non-homogeneous Option (*ADRIANO*), based on light signals produced in high transmittance optical glasses and scintillating plastic materials. The related *R&D* is conducted as part of the scientific program of Fermilab based, T1015 Collaboration.

2. Description of *ADRIANO* techniques

The *ADRIANO* technique (*A Dual-readout Integrally Active Non-segmented Option*), developed by *T1015*[1] Collaboration is intended to be used for High Energy as well as High Intensity experiments. However, the different requirements for the two classes of experiments have conducted to two separate designs, each optimized for that specific application.

ADRIANO for High Energy experiments. Most of the *ADRIANO* prototypes which we have designed and built for High Energy experiments have a full modular structure, with the base unit consisting of an individual cell of parallelepiped shape with $40 \times 40 \text{ mm}^2$ cross-section and either 15 cm or 25 cm length. The cell consists of a sandwich of scintillating fibers and high density, optical grade heavy glass. The glass behaves as an absorber and as an active medium at the same time, generating almost exclusively Čerenkov light. The scintillation and Čerenkov sections of *ADRIANO* are optically separated. Therefore, the two generated light signals are well separated, with minimal chance of cross-talk. We have considered various techniques to optically separate those two regions: white and silver coating of the glass, white coating, silver coating and aluminum sputtering of the scintillating fibers and, finally, a thin layer of Teflon between the glass plates and the array of scintillating fibers.

The scintillating fibers are either accommodated in grooves formed in the glass itself or in white plastic trays sandwiched among plates of glass. They run parallel to the longitudinal axis of the cell and are responsible for the generation of the scintillation component of the

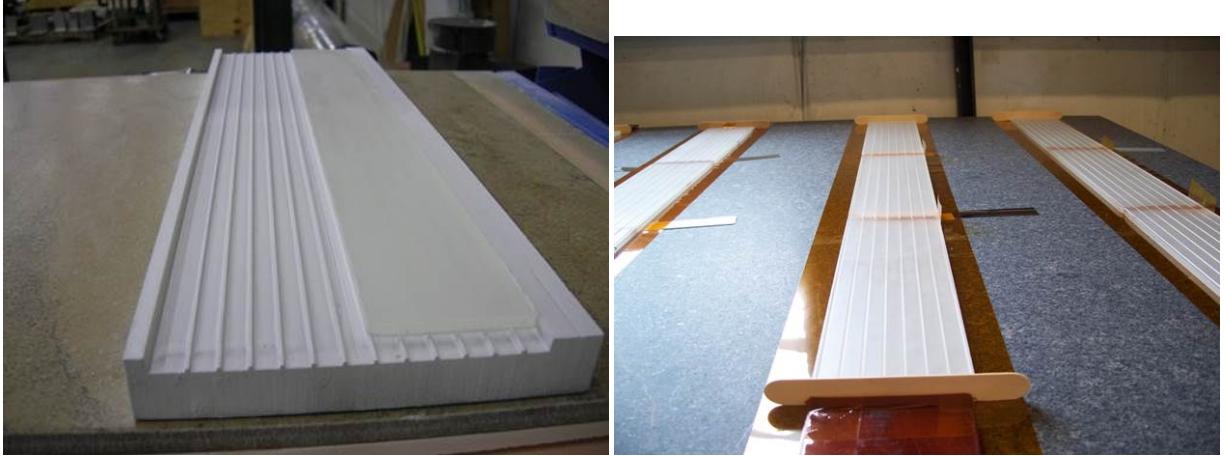


Figure 1. *Molding fabrication technology.*

dual-readout calorimeter. The pitch between nearby fibers is sufficiently small compared to the nuclear hadronic interaction length of the detector that the shower sampling fluctuations are well contained.

The Čerenkov light generated inside the glass is collected by WLS fibers running inside grooves parallel to the scintillating fibers and optically coupled to the glass by compounds formulated ad-hoc to match the large difference in the refractive indeces involved. The two light components are read out at the back of each cell with two distinct photodetectors. In some sense, *ADRIANO* is a spaghetti calorimeter with the passive absorber replaced by an active, transparent absorber made of heavy glass. Another advantage of *ADRIANO* relies on the fact that the heavy glass absorber can be used to detect electromagnetic showers in exactly the same ways as it has been done in the past with lead glass based electromagnetic calorimeters. The latters are known to be excellent *EM* calorimeters in terms of detection efficiency and energy resolution. Therefore, *ADRIANO* does not require a front electromagnetic section.

Several heavy glasses (mostly lead and bismuth based) have been tested, with the intent of comparing the Čerenkov light yield and propagation. Their refractive index ranges from 1.85 through 2.24 while the densities range from $5.5\text{g}/\text{cm}^3$ through $7.5\text{g}/\text{cm}^3$. Various construction techniques have been considered: diamond machining, precision molding, glass melting, laser drilling and photo-etching. However, only the former two have been used for the production of the eleven *ADRIANO* prototypes presented in this report. A picture of a 8 mm thick glass slice obtained with the precision molding technique is shown in Fig.1 .

Two new *ADRIANO* prototypes, each 10 cm wide and 105 cm long, have been built in 2014; both of them have been optimized for experiments at High Energy lepton colliders. The first prototype (*ADRIANO 2014A*) was constructed by alternating 10 layers of Schott SF57 lead glass plates, each 6.5 mm thick, with an equal number of thin (2 mm) scintillating plates, extruded at Fermilab's *Plastic Extrusion Facility*. The scintillating and Čerenkov lights from the individual plates was captured with optically coupled WLS fibers sitting in grooves running along the detector. The second prototype (*ADRIANO 2014B*) was built by stacking 10 layers of Schott SF57 lead glass plates, each 6.5 mm thick. A total of 26 grooves were formed in the glass plates using the precision molding technique. Twenty scintillating fibers and six WLS fibers were accommodated in those grooves, the former (optically separated from the glass) were responsible for the scintillating component of the detector while the latter (optically coupled to the glass) were used to capture the Čerenkov light. Both prototypes have been completely built at the Fermilab's *Thin Film Facility* and were exposed to a beam of particles shortly after their

construction. Preliminary results of the measurements are presented below.

A detailed description of the layouts of the above prototypes and their corresponding construction techniques will follow in an upcoming article.

A picture of *ADRIANO 2014A* and *ADRIANO 2014B* during the assembly phase is shown in Fig.2.

ADRIANO for High Intensity. *ADRIANO* prototypes intended for High Intensity experiments are optimized for larger light yield, rather than for high density, since they will operate mostly at lower energies and in the *EM* regime. They were, initially designed for the ORKA and REDTOP projects at Fermilab, where they would operate in the 5-500 *MeV* energy regime, but the layout can be properly optimized for any experiment with energy sensitivity above few MeV. In this case, we replaced the scintillating fibers with plates of thin (2 mm) and grooved extruded scintillator sandwiched between thicker (4.2 mm) heavy glass plates (Schott SF57), also grooved. Each plate is 10 cm wide and 37 cm long and it is formed with the molding technique described above. A picture of the two plates is shown in Fig.3

The light readout of each plates uses WLS fibers: 6 for the plastic plates and 13 for the glass plates. The larger number of WLS fibers per unit surface of glass ($0.031/\text{cm}^2$ vs $0.012/\text{cm}^2$ used in the High Energy version) captures more Čerenkov photons, at the expenses of a lower average density of the detector and an increased number of light sensors.

3. **ADRIANO readout system**

The scintillating and WLS fibers from each *ADRIANO* cell were bundled and routed each to a photodetector. In order to compare the performance of the light collection system in various situations we used three different photomultipliers (R647 and H3165 from Hamamatsu and P30CW5 from Sensetech) and two different SiPM ($4 \times 4\text{mm}^2$ square and $\varnothing 2.7\text{mm}$ round from FBK) for WLS fibers and only one type of SiPM ($4 \times 4\text{mm}^2$ square from FBK) for the scintillating fibers. When the PMT's were used, the fibers were routed through a plastic fixture and coupled to the photosensor window with custom made optical grease. In the case of SiPM's, we used either acrylic light concentrators (designed and produced by INFN Trieste) in direct contact with the fibers on one side and spaced $0.1\mu\text{m}$ from the active SiPM surface or we routed the fibers directly to the SiPM up to $0.1\mu\text{m}$ from the active SiPM surface. A picture of a INFN-Trieste light concentrators is shown in top left of Fig.4. The output of the SiPM and PMT used was digitized by the TB4 DAQ system developed at Fermilab. Among the features of the DAQ, the most relevant for our application are:

- 50Ω inputs
- 14 bit ADC;
- ~ 30 MHz bandwidth;
- ~ 212 MSPS digitizer;
- Up to 16 channels per Motherboard;
- Bipolar, so both positive (from SiPM) and negative (from PMT's) signals can be acquired simultaneously;
- Slow-control over USB, readout over 100 Mbit Ethernet.

4. **Results From the Test Beam at FTBF's**

The two prototypes for High Energy experiments: *ADRIANO 2014A* and *ADRIANO 2014B* were subject to several test beam during the year 2014, at the *FTBF Facility* of Fermilab (Batavia, US). A picture of the test beam setup is shown in Fig.4

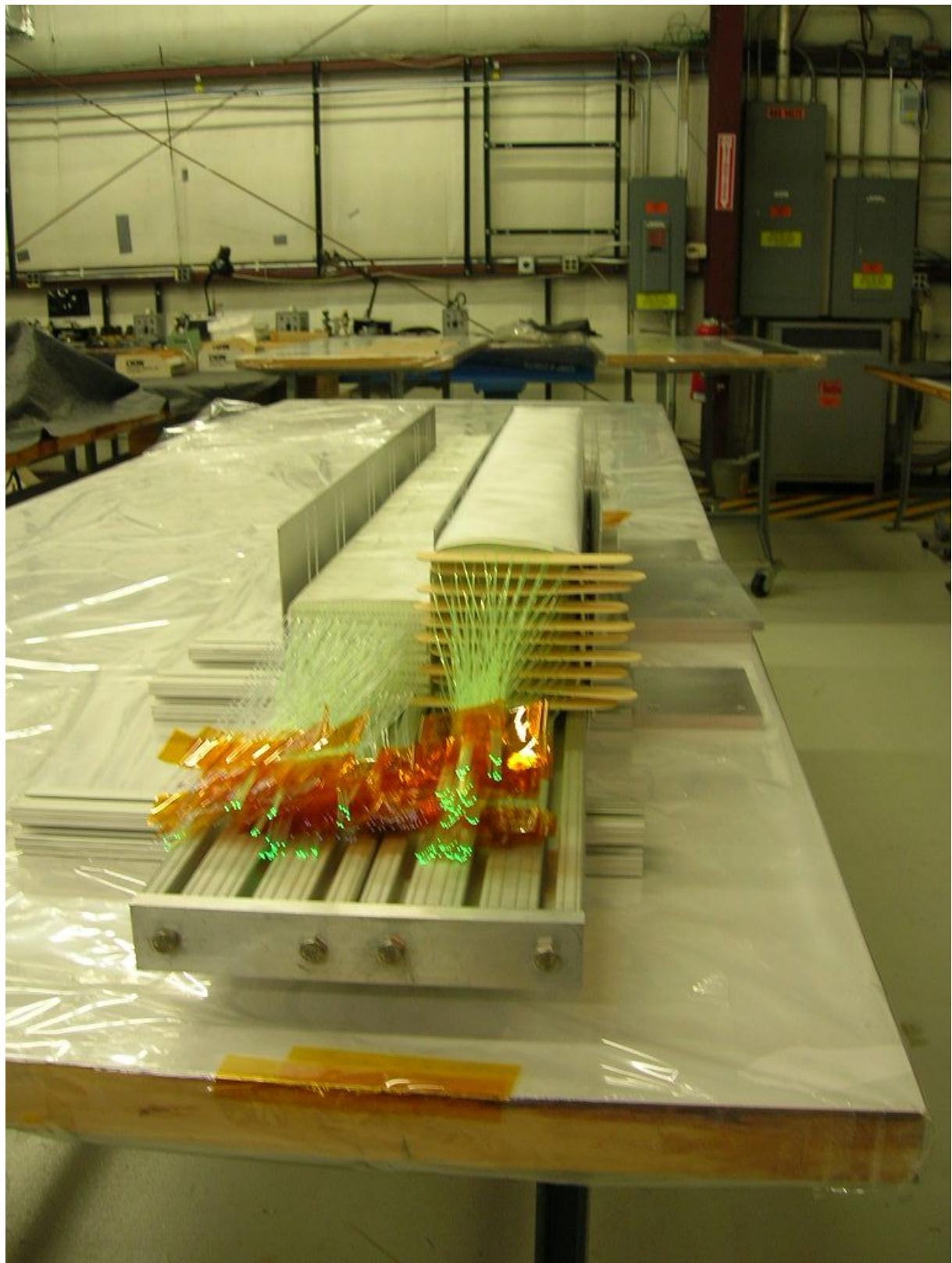


Figure 2. ADRIANO2014A (right) and ADRIANO2014B (left). During the assembly phase at Fermilab's Thin Film Facility.

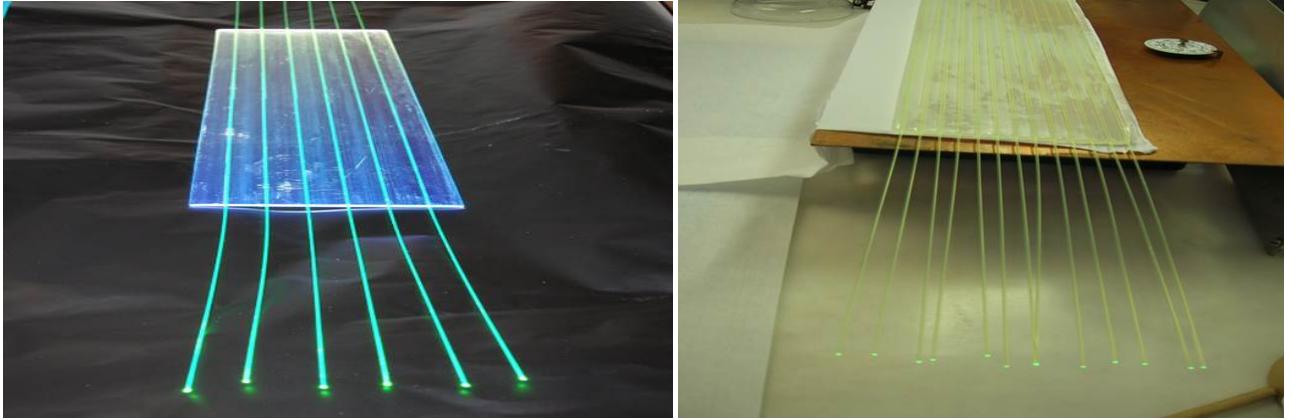


Figure 3. Plastic scintillator (left) and glass (right) plates in the ADRIANO for High Intensity experiments.

Prototype	Layout	Čerenkov L.Y.	Scintillation L.Y.
2014A	10 glass + 10 scintillating plates	354 pe/GeV	523 pe/GeV
2014B	10 glass plates + sparsified scintillating fibers	338 pe/GeV	356 pe/GeV

Table 1. Summary of light yields for *ADRIANO* 2014A (left) and *ADRIANO* 2014B modules tested in 2014 at Fermilab's FTBF.

The beam used was obtained by selecting secondary particles of known momentum from a 120 GeV proton beam impinged on a tungsten target. Data were taken at energies between 2 GeV and 1 GeV . The particle identification was provided by FTBF's double-angle Čerenkov systems. The scatters plot for electrons with momentum varying between 2 GeV and 16 GeV are shown in Fig.4 for *ADRIANO* 2014A (left) and *ADRIANO* 2014B (right).

Analogously, the ratio between the Čerenkov signal from the top half and the bottom half of the detector obtained from a vertical scan of a 4 GeV electron beam are shown in Fig.4 for *ADRIANO* 2014A (left) and *ADRIANO* 2014B (right).

The error bars associated with the measurements indicate that the Center of Gravity of a shower can be estimated with an error smaller than 1 cm . Finally, the scintillation and the Čerenkov light yields have been extracted from the data analysis, by subtracting the background induced by the pile-up of multiple events. The values obtained for the two detectors tested are summarized in Table 1.

The data indicate that the light yield is sufficient to guarantee that both techniques are capable of providing an hadronic energy resolution of $\sigma(E)/E \approx 30\%/\sqrt{E}$ in a detector volume which would contain most of the shower.

5. Summary

Since the start of ADRIANO *R&D* program, we were able to constantly improve the Čerenkov light yield by refining the construction techniques and the materials employed. A list of the Čerenkov light yield from the fifteen prototypes tested at FTBF so far is summarized in Table 1. The current limit for a $100 \times 90 \times 1050\text{ mm}^3$ prototype for High Energy is roughly 360 pe/GeV , obtained at a test beam at Fermilab in 2014 with the *ADRIANO* 2014A prototype.



Figure 4. Setup of a test beam at Fermilab's *FTBF* of *ADRIANO 2014A* and *ADRIANO 2014B* prototypes (2014)

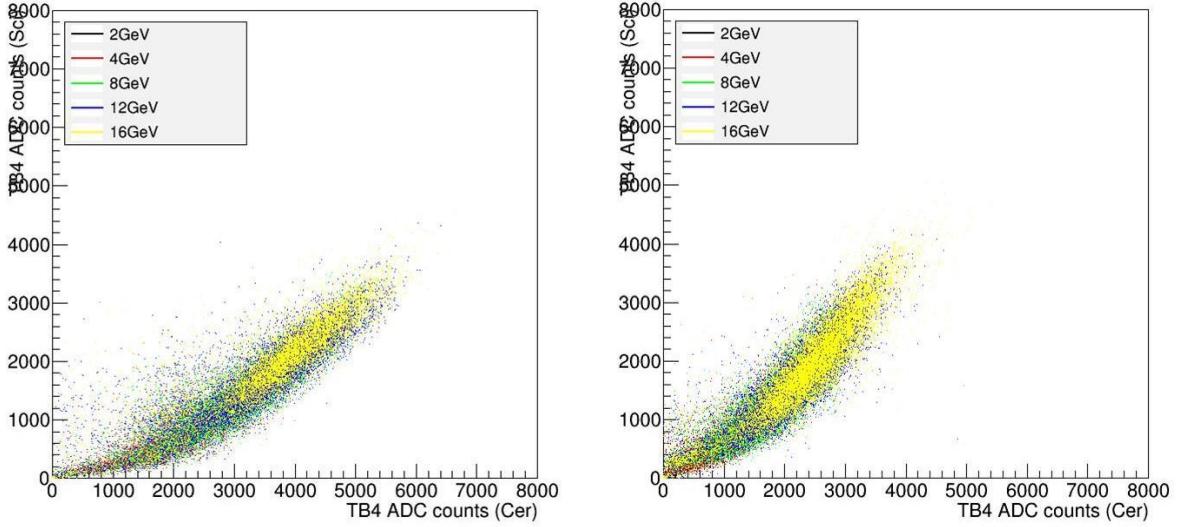


Figure 5. Scatter plots of the scintillating vs the Čerenkov light for ADRIANO2014A (left) and ADRIANO 2014B (right).

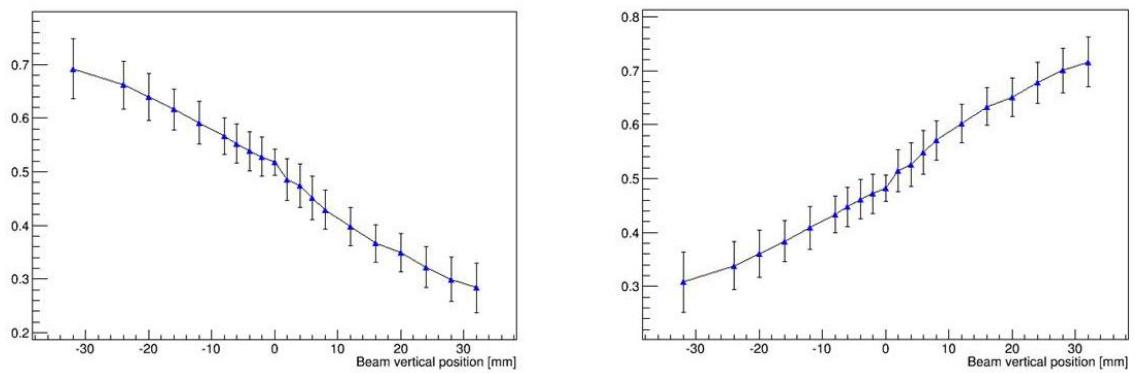


Figure 6. Scatter plots of the scintillating vs the Čerenkov light for ADRIANO2014A (left) and ADRIANO 2014B (right).

6. Future Prospects

The first five years of *R&D* performed by the T1015 Collaboration on the *ADRIANO* technique have already produced clear directions. Precision molding technique is, at present, the preferred fabrication technique since it has the potential of making quick (less than 30 minutes) glass slices with optical surface finish and with appropriate grooves. Nonetheless, we will keep exploiting other fabrication techniques as they might have other potential advantages when compared to precision molding. Photo-etching techniques, for example, are expected to be equally fast and low-cost, although they have quite severe chemical hazards associated with.

A great boost in *ADRIANO* development is currently obtained with Ohara sponsorship/partnership as they have provided bismuth glass strips of commercial optical glass ($6.6g/cm^3$, $nd = 2.0$) and strips of an even denser experimental glass with density of $7.54g/cm^3$ and refractive index of 2.24.

Prototype #	Layout	Glass	g/cm ³	L.Y	Notes
1	5 slices, machine grooved, unpolished, white	Schott SF57HHT	5.6	82	SiPM readout
2	5 slices, machine grooved, unpolished, white, v2	Schott SF57HHT	5.6	84	SiPM readout
3	5 slices, precision molded, unpolished, coated	Schott SF57HHT	5.6	55	15 cm long
4	2 slices, ungrooved, unpolished	Ohara BBH1	6.6	65	Bismuth glass
5	5 slices, scifi silver coated, grooved, clear, unpolished	Schott SF57HHT	5.6	64	15 cm long
6	5 slices, scifi silver coated, grooved, clear, unpolished	Schott SF57HHT	5.6	120	improved version
7	10 slices, white, ungrooved, polished	Ohara PBH56	5.4	> 30	DAQ problems
8	10 slices, white, ungrooved, polished	Schott SF57HHT	5.6	76	
9	5 slices, scifi Al sputter, grooved, clear, polished	Schott SF57HHT	5.6	30	2 wls/groove
10	5 slices, ungrooved, polished	Schott SF57HHT	5.6	158	2012 version
11	2 slices, plain	Ohara experimental	7.5	—	DAQ problems
12	ADRIANO for ORKA - barrel (10 layers)	Schott SF57	5.6	4000	Analysis in progress
13	ADRIANO for ORKA - endcap (10 layers)	Schott SF57	5.6	4000	Analysis in progress
14	ADRIANO 2014A	Schott SF57	5.6	354	105 cm long prototype
15	ADRIANO 2014B	Schott SF57	5.6	338	105 cm long prototype

Table 2. Summary of the Čerenkov light yields for ADRIANO modules from seven test beams occurred from 2011 through 2014.

Currently, one new *ADRIANO* prototypes is under construction at Fermilab aimed at High Energy experiments (high material density and moderate light yield). The layout of the new prototype has been designed based on the experience and the results obtained from the prototypes built and tested in 2014. The goal is that of achieving an excellent light yield, similar to that of *ADRIANO* 2014A, and a large average density, characteristic of *ADRIANO* 2014B prototype. A test beam for the new detector is already scheduled in December 2015. For the medium future, we planned to continue to design and build new modules and, consequently, to augment the volume of the existing setup for a better shower containment.

7. Conclusions

In this report we have presented the status of the R&D activity performed by T1015 Collaboration on the *ADRIANO* dual-readout technique. Two new detectors have been built and tested in 2014 bringing the total number of prototypes to fifteen. Preliminary results from a test beam at FTBF have been reported. The Čerenkov light yield we have obtained from most of the detector tested so far is more than adequate for an hadronic calorimeter with an energy resolution of $\sigma(E)/E \approx 30\%/\sqrt{E}$ or better. Our goal is to increase the light yield to a level where the Čerenkov light yield of *ADRIANO* can be used to detect also electromagnetic particles. Hardware *R&D* and Monte Carlo simulations are in an advanced state and constantly providing directions in the design of new prototypes. Furthermore, current results by T1015 obtained from several test beams have proved that Čerenkov light readout from heavy glasses with a WLS light capturing technique is feasible and provides equal or better results than traditional methods typically employing large area PMT's directly coupled to the glass. Correctly matching calorimetric techniques with SiPM and Front End Electronics is also crucial for a good performance of the detector. T1015 will address these issues in the future and it will exploit new, glass-based, calorimetric techniques which will also include scintillating heavy glasses.

8. Acknowledgments

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