

Liquid scintillator tiles for high radiation environments

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Abstract

Future experiments in high energy and nuclear physics may require large, inexpensive calorimeters that can continue to operate after receiving doses of 50 Mrad or more. We present the results of a study of a scintillator tile based on EJ-309 liquid scintillator using cosmic rays, test beam, and ^{60}Co irradiations that shows little degradation of light output under irradiation.

Keywords: organic scintillator, liquid scintillator, radiation hardness, calorimetry

1. Introduction

Sampling calorimeters using plastic scintillator tiles with wavelength-shifting (WLS) fibers as their active element, such as the CDF plug calorimeter [1] and the CMS Barrel [2] and Endcap [3] hadron calorimeters, are popular due to

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5 their low cost and ease of construction. Plastic scintillator is available com-
 mercially from companies such as St. Gobain and Eljen Technology. When
 irradiated, however, the performance of plastic scintillator and WLS fibers de-
 teriorates; light self-absorption (yellowing) increases and light output decreases.
 The resulting loss of light output for this kind of tile has been studied using
 10 irradiations from electron linacs and ^{60}Co sources [4, 5]. Generally, the light
 output decreases exponentially with dose, with an decay constant on the order
 of a few Mrad. Future high energy and nuclear experiments, however, may
 have to operate in environments that will deliver doses of tens of Mrad. Previ-
 ous studies of liquid scintillator have shown little decrease of light output with
 15 dose [6, 7, 8]. In this paper, we present the design and optimization of a liquid
 scintillator tile that can operate in this kind of environment. An earlier liquid
 tile design is described in [9].

2. Tile design

Our tile is based on EJ-309 scintillator, from Eljen Technology, which uses
 20 naphthalene as the substrate with wavelength shifting additives. EJ-309 has a
 light output that is 75% of anthracene, a wavelength of maximum emission of
 424 nm, a refractive index of 1.57, and a flash point of 144° C. The high flash
 point is important for its suitability for a collider environment.

The design of a tile to hold the liquid needs to consider light collection
 25 efficiency, light collection uniformity, and cost. The container should not leak,
 and there should not be interactions between the container and its contents that
 degrade the light output over time or compromise the integrity of the container.
 Figure 1 shows the mechanical construction of our prototype. The case is made
 of aluminum. Two transparent quartz support tubes run through the liquid and
 30 can hold either a WLS fiber or liquid wavelength shifter. When a WLS fiber was
 used, the end of the fiber not connected to the photodetector was coated with Al
 to increase the light output unless otherwise noted. The support tube is sealed
 to the case with a Viton fluoroelastomer o-ring. The thicknesses of the top and

bottom Aluminum plates are 0.5 mm. The total internal volume is 88 mm x
35 88 mm x 4 mm. The inner surface of the container is a lapped and polished Al-
6061 available from McMaster Carr. The material comes with a plastic coating
that can be used to maintain its mirror quality during the machining process
and then is removed before the welding step. The liquid was transferred into
the container in an inert atmosphere, as contamination with Oxygen decreases
40 the light output.

Several variations on this design were constructed. For the default design,
the thickness of the liquid is 4 mm. A version with a 6 mm thickness was also
made. The default support tubes, from Atlantic International, were quartz with
an inner diameter of 1.3 mm and were used with Kuraray Y-11 fiber (doping of
45 200 ppm), double-clad. The index of refraction was measured at the Quattrone
Nanofabrication Facility at the University of Pennsylvania to be **need jeff's num-
ber**. As an alternative, two types of Quartz tubes filled with liquid wavelength
shifter (capillaries) were also used. One set, of ordinary quartz, had an outer di-
ameter of 2 mm, an inner diameter of 1 mm, and a measured index of refraction
50 of **need Jeff's number**. Another used special radiation-resistant quartz and had
an outer diameter of 1 mm and an inner diameter of 0.4 mm, with a measured
index of **need jeff's number**. The liquid wavelength shifter was a prototype
material from Eljen, and is not yet a commercial item. The liquid wavelength
shifter has an emission maximum from between 481 and 492 nm and a decay
55 time between 2 and 8 ns. The solvent was the same as that used for EJ-309.
Sapphire tubes were also tested with both liquid and plastic wavelength shifter.

In what follows, the results shown are for the mirrored tile with 4 mm thick-
ness, ordinary quartz support tubes, and a 0.9 mm diameter Y-11 WLS fiber,
unless otherwise stated.

60 **3. Light yield and uniformity as measured in test beam**

The light yield and uniformity of the tiles was measured in the H2 test
beam facility at CERN using 120 GeV muons. The trigger required coincidence

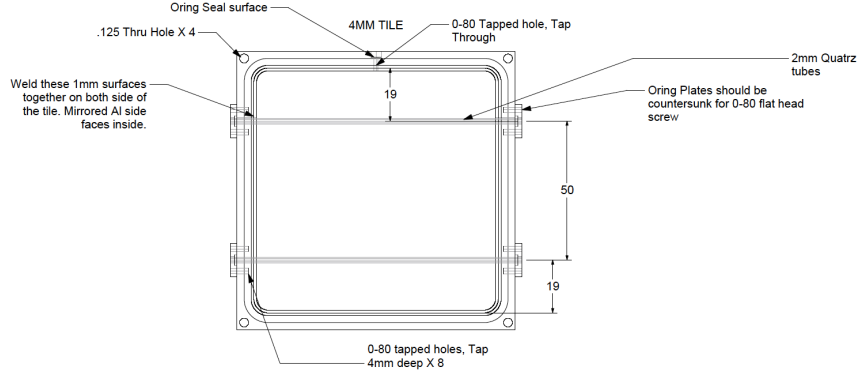


Figure 1: Mechanical design of a liquid scintillator tile. Units are [mm].

of two out of four plastic scintillator hodoscopes. The effective beam cross sectional area, after trigger requirements, was $14 \times 14 \text{ cm}^2$. The positions of the
65 muons were measured with four wire chambers. The position obtained from the counter closest to the prototype was used. We also required the signal in each wire chamber be consistent with that of a single muon, and that the difference in positions in sequential chambers be consistent within uncertainties. As many groups were using the same test beam, there was material upstream of our
70 counters. For some runs, several steel blocks were used to support experiments upstream of our counters. Because the muons were high energy, the probability of a muon-induced shower was non-negligible. (This was verified later at a test beam at FNAL that had a cleaner beam line, by varying the material in front of the tile and through simulations with varying amounts of material.) We present
75 here the results from the runs and tiles with the smallest upstream material.

The WLS fiber was connected to a clear fiber using a connector designed at FNAL. The clear fiber was lead away from the beam line. The light output was measured using a Hamamatsu R7600U-200-M4 photomultiplier tube and a custom ASIC that integrates and digitizes the resulting charge, called the “QIE” [10]. The photomultiplier has a peak quantum efficiency of 40% at a wavelength of 400 nm and produces a clear single photoelectron (pe) peak. The integrated charge is digitized every 25 ns. Ten digitizations were recorded per muon trigger. The sum of the signal in the 4th to 7th sample was used.

The average number of pe’s produced per minimum ionizing particle (mip) was estimated by doing a Gaussian fit to the peak centered on the pedestal. The mean number of pe’s was calculated using the fraction of events in this peak, assuming a Poisson distribution. The nominal tile produced 1.7 pe’s per mip. A plastic tile (SCSN-81 with Y-11 fiber) with dimensions 10 cm x 10 cm x 4 mm tested at the same time gave 1.8 pe/MIP. The results have a systematic uncertainty related to the handling of the events with showering muons. We evaluate this uncertainty by looking at the results after truncating the distribution at around 25 pe’s (2000 adc counts). The results were stable to within 5%. In addition, runs taken with varying amounts of material in front of our detector (up to 20 cm of steel) resulted in a 15% variation in light yield. We therefore take a 16% uncertainty due to upstream material.

The uniformity of the light collection was also studied at the CERN test beam. Figure 2 shows the fraction of events with at least 1 pe versus the impact position of the mip along the axis parallel to the support tubes (left) and perpendicular to the support tubes (right). As expected, there is little dependence on the coordinate parallel to the support tubes. The light yield does depend on the perpendicular distance. The light collection efficiency is maximum for muons near the WLS fiber and is approximately 20% lower for muons in the center or edges of the tile. For most hadron calorimetry applications, we verified through simulation that this degree of non-uniformity would not adversely affect jet resolutions.

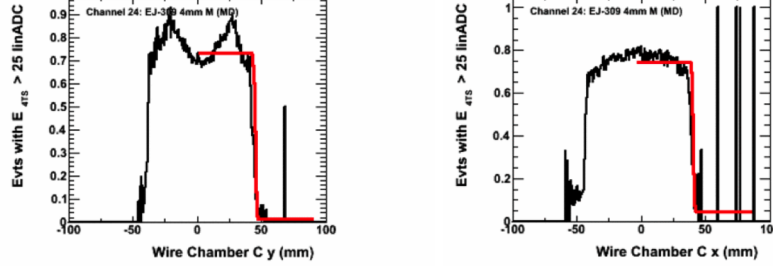


Figure 2: For the nominal liquid tile, fraction of mips with at least one pe as a function of the impact position of the mip along the axis parallel to the support tubes (left) and perpendicular to the support tubes (right).Geng Yuan will remake to publication quality

4. Light yield dependence on tile parameters

The dependence of the light yield on variations in the design parameters was studied using cosmic ray data taken at the University of Maryland. Scintillator-based counters above and below the tile were used for triggers. The tile light output was measured using a Hamamatsu R7600U-200-M4 photomultiplier tube. Fibers were connected to the tube using optical glue. Data was collected with a Tektronix MSO 5204 oscilloscope. No attempt was made to select minimum ionizing muons. The muons thus are low energy and will produce more light than those studied at the CERN test beam.

We found an average of 2.88 ± 0.05 pe for the nominal tile. A similar tile but without the mirroring yielded 1.98 ± 0.03 pe, a reduction of a factor of 1.45. A tile with a 6 mm thickness of liquid, non-mirrored, yielded 2.61 ± 0.05 pe, an increase over the 4 mm non-mirrored tile of a factor of 1.32. Figure 3 shows the collected charge (arbitrary units) for the three different configurations.

The light yield was also studied using a capillary, filled with liquid WLS, instead of a quartz tube containing plastic WLS, since plastic WLS is susceptible to radiation damage. The capture efficiency of the WLS for the two different configurations depends crucially on the index of the surrounding media. For the WLS fiber, there is an air gap with an index of 1. For the capillary, the liquid WLS is instead bordered by quartz, with an index of **jeff's number**. The

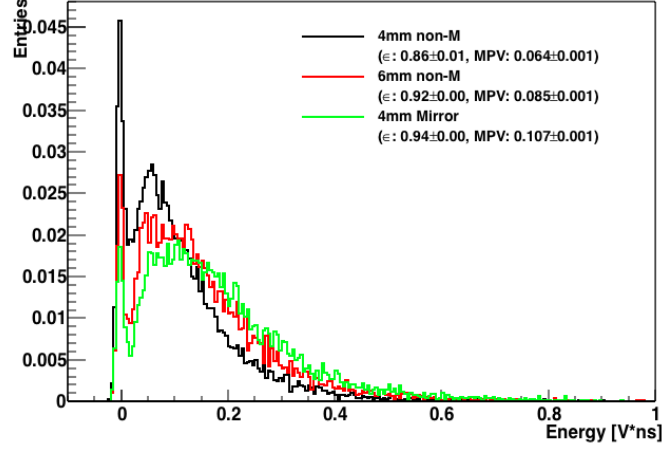


Figure 3: Comparison between the light output (arbitrary units) of liquid scintillator tiles with different thickness and different treatment of the aluminum surface in contact with the liquid scintillator. The light is readout with the same 0.9 mm-thick Y11 plastic WLS fiber. The three distributions are normalized to have the same number of events in the pedestal. Geng Yuan will remake to publication quality. I hate the normalization of these plots. can we normalize to number of muons? also, what is mpv? needs to be clear

plastic and liquid WLS have very similar indices of refraction (1.57). In both cases, the shifted light propagates in the WLS, but the capture efficiency is higher for the lower index air. Figure 4 shows the charge collected (in arbitrary units) from cosmic muons for the two different configurations. The fraction of events in the pedestal, which is the Gaussian-shaped peak at low charge, can be used to calculate the fraction of muons producing at least one pe (light collection efficiency) and the mean number of pe's per muon. The light collection efficiency is 92% for the plastic WLS and 45% for the liquid. The light yield for the liquid is half that of the plastic. The light collection efficiency with the liquid could be improved if lower index quartz could be found.

Finally, we tested the performance of the same tile, 4 mm-thick, with a mirrored aluminum surface, as a function of the thickness of the readout plastic WLS fiber. We tested three plastic fibers, with a thickness of 0.5 mm, 0.9 mm,

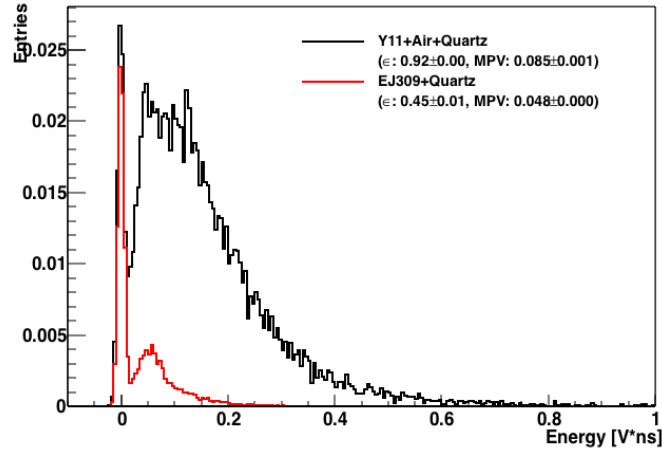


Figure 4: Comparison between the light output of a liquid scintillator tile equipped with a plastic WLS fiber, and a capillary filled with liquid WLS. The two distributions are normalized to have the same number of events in the pedestal. Geng Yuan will remake to publication quality, and will make a more sensible normalization since i hate this normalization to the pedestal. why not normalize to the same number of muons?

and 1 mm. We measured that the higher the fiber thickness, the higher the
140 efficiency and light output, as shown in Figure 5. This would be much more useful as a plot of pes versus fiber thickness. If we can not get this, I say remove it.

5. Radiation hardness tests

Several different tests were made using irradiations with a ^{60}Co source at the
145 University of Maryland. Performance of the tile under irradiation in a proton-proton collision environment will be the subject of a future paper.

A dark-glass vial containing 125 ml of liquid scintillator was irradiated with γ -rays to a dose of 50 Mrad, at a dose rate of 1 Mrad/hr. Figure 6 compares the integrated charge (arbitrary units) from the same tile when filled with unirradiated liquid and irradiated liquid.
150 The efficiency and light output from the two

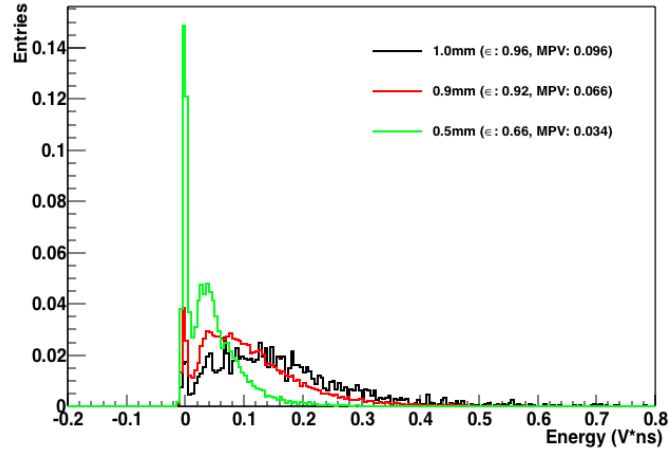


Figure 5: Comparison between the light output of liquid scintillator tiles readout with plastic WLS fibers with different thickness. The three distributions are normalized to have the same number of events. Geng Yuan will remake to publication quality

measurements are consistent within the uncertainty, indicating that EJ-309 is radiation-tolerant to γ -ray irradiations.

I want to try irradiating an entire tile with the rad hard 1mm tubes from Randy and put the results here as well.

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6. Comparison with simulation, and optimization

We use the GEANT4 [11] package to simulate the optics of our tile. GEANT4's optical package includes simulations of refraction, reflection, wave length shifting, and light attenuation. A variety of options for the reflection are available. We used the “Specular Spike” option for the Al and an absorption length of 2m for the EJ-309. When simulating the WLS fiber, an air gap was included between the fiber cladding and the support tube, while no such gap exists for the simulation of the capillary. An index of refraction of 1.57 is used for the EJ-309. The index for sapphire used was 1.77. For quartz, values between 1.46

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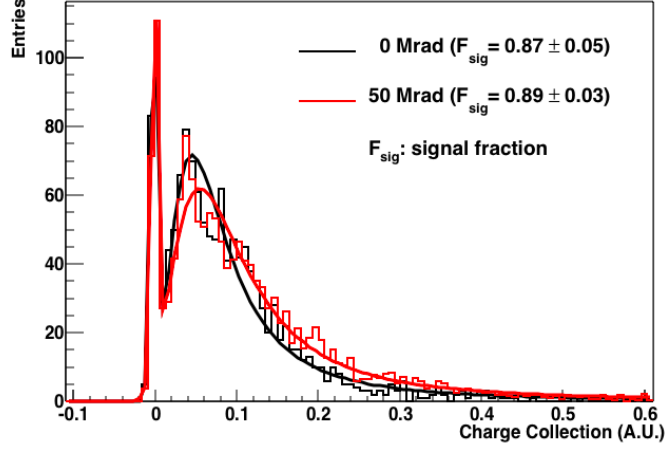


Figure 6: Comparison between the light output of a liquid scintillator tile filled with unirradiated (black) and irradiated (red) liquid scintillator. The two distributions are normalized to have the same number of events in the pedestal. Geng Yuan will remake to publication quality

165 and 1.55 were used. Photons are generated at random positions inside the liquid volume, with a wavelength corresponding to the emission maximum of EJ-309.

As shown in Figure 7 left, we find the simulation reproduces the light collection non-uniformity when a reflectivity of 0.9 is used for the mirrored Al.

We find that the light collection efficiency is a strong function of the reflectivity of the Al (Figure 7 right).
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We find the best light collection comes when the support tube has the lowest possible index of refraction for liquid WLS. The opposite is true for a fiber with an air gap (and plastic WLS). For a 1 mm diameter for the WLS, the light collection efficiency increases by a factor of 3.57 going from an index of 1.55 to
175 1.46 for liquids. Presumably this difference would decrease as the reflectivity of the Al increases. For a fiber with an air gap, the efficiency decreases by a factor of 1.42 going from an index of 1.77 to 1.46.

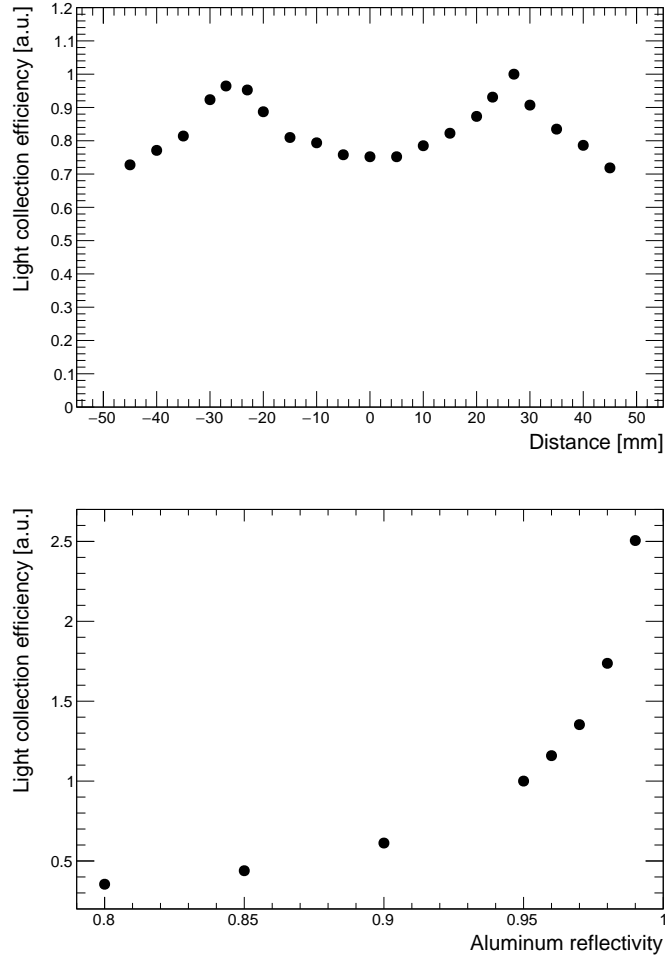


Figure 7: (left) Ratio of light yield to maximum light yield from simulated tile as a function of the distance perpendicular to the support tubes, normalized to the efficiency at the position of the support tubes. (right) Light collection efficiency vs Aluminum reflectivity, normalized to a reflectivity of 0.95.

7. Conclusions

We presented results for a liquid scintillating tile using WLS fiber readout.

For our nominal design, 1.7 ± 0.2 pe's were produced for minimum ionizing particles.

8. Acknowledgments

The authors would like to thank Randy Ruchti of Notre Dame for providing the capillaries and both Randy and Chuck Hulbut of Eljen Technologies for
185 advice in general on liquids. Yasar Onel's group at the University of Iowa for help with the test beam. We would like to thank Eric Johnston from the Quattrone Nanofabrication Facility at the University of Pennsylvania for measuring the indices of refraction of our support tubes. The authors would like to thank
various people at the University of Maryland's Nuclear Reactor and Radiation
190 Facilities group for assistance with the irradiations. We would like to thank the University of Maryland FabLab, especially who helped, for help with fiber sputtering. This work was supported in part by U.S. Department of Energy Grant DESC0010072.

References

- 195 [1] S. Aota *et al.*, A scintillating tile/fiber system for the cdf plug upgrade em calorimeter, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 352 (3) (1995) 557 – 568. doi:[http://dx.doi.org/10.1016/0168-9002\(95\)90005-5](http://dx.doi.org/10.1016/0168-9002(95)90005-5).
- 200 [2] S. Abdullin *et al.*, Design, performance, and calibration of cms hadron-barrel calorimeter wedges, The European Physical Journal C 55 (1) (2008) 159–171. doi:[10.1140/epjc/s10052-008-0573-y](http://dx.doi.org/10.1140/epjc/s10052-008-0573-y).
- [3] The CMS hadron calorimeter project: Technical Design Report, Technical Design Report CMS, CERN, Geneva, 1997.
- 205 [4] V. Hagopian, I. Daly, Radiation damage of fibers, AIP Conference Proceedings 450 (1) (1998) 53–61. doi:<http://dx.doi.org/10.1063/1.56958>.
- [5] A. Byon-Wagner, Radiation hardness test programs for the {SDC} calorimeter, Radiation Physics and Chemistry 41 (12) (1993) 263 – 271. doi:[http://dx.doi.org/10.1016/0969-806X\(93\)90064-2](http://dx.doi.org/10.1016/0969-806X(93)90064-2).

- 210 [6] C. Zorn, S. Majewski, R. Wojcik, C. Hurlbut, W. Moser, Preliminary study
of radiation damage in liquid scintillators, Nuclear Science, IEEE Transactions on 37 (2) (1990) 487–491. doi:10.1109/23.106666.
- [7] J. Klein, J. Gresset, F. Heisel, G. Laustriat, Effets des rayonnements- sur
les caracteristiques des scintillateurs organiques, The International Journal
215 of Applied Radiation and Isotopes 18 (6) (1967) 399 – 406. doi:http://dx.doi.org/10.1016/0020-708X(67)90143-3.
- [8] I. Berلمان, The effect of massive Co^{60} doses on the light output of a scintillator solution, Radiological Physics Division Semiannula Report for July through December 1957.
- 220 [9] J. Marchant, B. Baumbaugh, L. Ciastko, B. Dolezal, A. Heering, C. Hurlbut, M. McKenna, T. Pearson, R. Ruchti, A. Williams, Liquid-based scintillators for particle physics, in: Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE, 2010, pp. 10–13. doi:10.1109/NSSMIC.2010.5873708.
- 225 [10] T. Shaw, A. Baumbaugh, A. Boubekur, J. Elias, J. Hoff, S. Holm, S. Los, C. Rivetta, A. Ronzhin, J. Whitmore, T. Zimmerman, R. Yarema, Front end readout electronics for the cms hadron calorimeter, in: Nuclear Science Symposium Conference Record, 2002 IEEE, Vol. 1, 2002, pp. 194–197 vol.1. doi:10.1109/NSSMIC.2002.1239297.
- 230 [11] S. Agostinelli, et al., Geant4a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506 (3) (2003) 250 – 303. doi:http://dx.doi.org/10.1016/S0168-9002(03)01368-8.