Performance of a Highly Granular Scintillator-SiPM Based Hadron Calorimeter Prototype in Strong Magnetic Fields

Christian Graf
Max-Planck-Institute for Physics, Munich, Germany
Email: cgraf@mpp.mpg.de
for the CALICE Collaboration

Abstract—Within the CALICE collaboration, several concepts for the hadronic calorimeter of a future linear collider detector are studied. After having demonstrated the capabilities of the measurement methods in "physics prototypes", the focus now lies on improving their implementation in "engineering prototypes", that are scalable to the full linear collider detector. The Analog Hadron Calorimeter (AHCAL) concept is a sampling calorimeter of tungsten or steel absorber plates and plastic scintillator tiles read out by silicon photomultipliers (SiPMs) as active material. The front-end chips are integrated into the active layers of the calorimeter and are designed for minimizing power consumption by rapidly cycling the power according to the beam structure of a linear accelerator. The versatile electronics allows the prototype to be equipped with different types of scintillator tiles and SiPMs. A prototype with ∼2200 channels, equipped with several types of scintillator tiles and SiPMs, was tested with muons and electrons in a 1.5 T magnet at the CERN SPS in May 2017 to establish the operational stability with power pulsing and the overall detector performance in a magnetic field.

I. INTRODUCTION

The physics at future high-energy lepton colliders, with its requirement for a jet energy reconstruction with unprecedented precision, is one of the primary motivations for the development of highly granular calorimeters by the CALICE collaboration. The detector concepts for the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) rely on Particle Flow Algorithms (PFA) [1], which are capable of achieving the required resolution. This event reconstruction technique requires highly granular calorimeters to deliver optimal performance.

One of the technologies developed within CALICE is the Analog Hadron Calorimeter AHCAL [2]. It is based on active elements consisting of 3 cm × 3 cm plastic scintillator tiles individually read out by silicon photomultipliers (SiPMs) in a steel absorber structure with approximately 20 mm of absorber material between each active layer. A full "physics prototype", which has been extensively tested in particle beams at DESY, CERN and Fermilab, has demonstrated the capabilities of this technology, achieving competitive single hadron energy resolution [3] and the two-particle separation required for good PFA performance [4]. The prototype was also successfully tested with tungsten absorbers.

II. THE CALICE ANALOG HADRON CALORIMETER ENGINEERING PROTOTYPE

With the establishment of the viability of the AHCAL concept, the focus is now shifting from the study of the physical performance characteristics of such a detector to the demonstration of the detector performance while satisfying the spatial constraints and scalability requirements of collider experiments. This is the goal of the "engineering prototype". This prototype uses electronics fully embedded in the active layers to minimize space requirements for interfaces outside of the active detector volume, and is based on scintillator tile designs well-suited for mass production and automatic assembly. In a first iteration of studies, different scintillator tile designs and different photon sensors were investigated [5], before converging on a design using SMD-style SiPMs and scintillator tiles with a central dimple, as shown in fig. 1, to allow fiberless coupling of the scintillator to the SiPM [6].

The basic unit of the active elements is the HCAL Base Unit HBU, with a size of 36 cm × 36 cm, holding 144 scintillator tiles controlled by four ASICs (SPIROC [7]). A key element of the electronics is the capability for power-pulsed operation to reduce the power consumption and eliminate the need for active cooling, making use of the low duty cycle in the linear collider beam time structure. The electronics also provide a cell-by-cell auto trigger and time stamping on the few ns...
level in test beam operations. In operating conditions with shorter data-taking windows closer to the bunch train structure of linear colliders, sub-ns time resolution is available.

Different absorber structures are used to test the HBUs of the engineering prototype. One of them, shown in fig. 2, is a compact 15 layer structure made of high-quality non-magnetic stainless steel, housing one HBU per layer, deep enough to contain electromagnetic showers. This allows for a precise evaluation of the detector response with electrons. HBUs installed in this structure were recently exposed to electron beams at DESY, illustrated by the event display shown in fig. 3.

To evaluate the stability of the readout with power pulsing and in the presence of a strong magnetic field, single HBUs were tested with power pulsing enabled in a 2 T magnetic field at DESY. Figure 4 demonstrates that the photon sensor gain remains stable with power pulsing and within a magnetic field. The small shift in the positions of the individual photon peaks between the case with and without magnetic field are due to the difference in temperature for the datasets.

III. TEST-BEAM CAMPAIGN IN MAY 2017

As a next step to validate the engineering prototype a test-beam campaign was carried out to evaluate the performance of the prototype in a magnetic field. For this test, the compact stainless steel absorber structure, introduced above, was used, equipped with 15 HBUs. The steel stack accounts for approximately $17X_0$ and 1.8 nuclear interaction lengths.

In the first six layers of the prototype new HBUs equipped with surface-mounted SiPMs from Hamamatsu are installed. The scintillators are the injection-molded polystyrene tiles shown in fig. 1. Layer 7 uses an HBU with previous generation surface-mounted SiPMs. Layers 8 to 15 are equipped with older HBUs showing good quality in former test-beam campaigns using SensL SiPMs and a different tile design optimized for the direct coupling of the photon sensor to the tile side [5].

The detector was mounted in a magnet located at the H2 beam line at SPS (CERN), as shown in fig. 5. During the ramp up of the magnet to its design current, which provides a field at the center of the magnet of 3 T, the magnet had to be turned off, because of a failure of a circuit breaker. The detector was running without incidents up to the highest magnetic field observed of about 2.4 T. Afterwards, the magnet could be operated at a maximum magnetic field of 1.5 T for the remaining duration of the test-beam campaign. During one week of data taking, data of 120 GeV muons and 10, 20, 30, 40 and 60 GeV electrons has been recorded with and without magnetic field.

IV. RESULTS

The analysis of the data is still work in progress. Here, only selected first results are presented.
Fig. 5. Placement of the prototype in the magnet during the test-beam campaign. The view is on the back of the detector with the direction of the beam facing out of the image plane. The magnetic field is oriented from left to right.

Fig. 6. Hit map of electromagnetic showers of 10 GeV electrons in all 15 layers of the prototype.

Fig. 7. Hit position in y-direction of 10 GeV electrons with and without 1.5 T magnetic field.

Fig. 8. Total number of detected hits 10 GeV electron events with and without 1.5 T magnetic field.

A. Hit Distributions

Figure 6 shows the distribution of hits for each layer of the detector for 10 GeV electrons. All readout chips are working and only very few dead channels are observed. One can clearly see the average shape of the electromagnetic shower with most parts confined within the detector. In general, the detector shows a good homogeneity in hit detection efficiencies and noise rates.

Figure 5 shows a view on the setup facing the back of the detector. In this view, the magnetic field is oriented in horizontal direction from left to right. By comparing the distribution of the hit position with and without magnetic field in y-direction, as shown in fig. 7, the effect of the magnetic field on the electromagnetic shower can be observed. A shift of approximately half a tile to smaller values on the y-axis is visible, as well as a slight broadening of the shower. As expected, the hit distribution in x-direction shows no change due to the magnetic field. The broadening of the electromagnetic shower goes along with an increase in the overall number of detected hits per event of about 10% as shown in fig. 8.

B. Energy Response

It is already known from the literature that the light yield of a scintillator is enhanced within a magnetic field [8]. For polystyrene based scintillators with wavelength shifting fibers an increase in light yield of approximately 6% was observed in a 2 T magnetic field [9].

For the prototype an increase of approximately 4% is observed in the detector response for each channel for 120 GeV muons in a magnetic field. This effect adds up with the effect of more observed hits in an electromagnetic shower and a longer geometrical path of particles bend by the magnetic field, such that the energy response of an electromagnetic shower is increased by roughly 10% in a magnetic field.

C. Muon Time Resolution

In order to check the stability of time measurements with a magnetic field the time distribution of muons is investigated. Figure 9 shows the time distribution of 120 GeV muon data of runs taken before, during and after the magnetic field. The distribution stays stable except for a slight broadening that is observed during and after the magnetic field. Whether this is
due to an effect of the magnetic field in the electronics, or a specific time dependent effect within certain runs, induced for example by changing environmental conditions needs to be investigated.

V. FULL PROTOTYPE CONSTRUCTION

A full hadronic prototype of the AHCAL with approximately 23,000 electronic channels, organized in 160 HBUs on 40 layers, is currently under construction and will prove the scalability of the technology to a significant part of a full detector. It uses Hamamatsu MPPC S13360-1325PE photon sensors and the injection-molded polystyrene scintillator tiles, as shown in fig. 9. The scintillator tiles are wrapped in reflective foil by a robotic procedure prior to automatic placement on the HBU board with assembled photon sensors. The full hadronic prototype will see first beam in 2018.

VI. CONCLUSION

The engineering prototype of the AHCAL is an important tool to verify the technologies developed in the CALICE collaboration for the construction of a highly granular hadronic calorimeter for a future linear collider detector. As one step towards this goal, a test-beam campaign was carried out in order to test the performance of the prototype in a strong magnetic field. Data of muons and electrons at different energies were taken with and without a magnetic field of 1.5 T. A broadening of the shower due to the magnetic field is clearly visible. The detector response with the magnetic field is increased by roughly 10%. This effect is a combination of an increased light yield of the scintillator, more observed hits in the event and a longer path of the particles traversing the scintillator due to the bending in the magnetic field. The increase in light yield of the scintillators of roughly 4% is in agreement with previous observation in literature. No significant influence of the magnetic field on the time measurement is being observed. As a next step the construction of a large prototype with 23,000 channels is currently ongoing and will be tested in 2018.

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