Construction of a technological semi-digital hadronic calorimeter using GRPC

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Abstract. A high-granularity semi-digital Hadronic calorimeter using GRPC as sensitive medium is one of the two HCAL options considered by the ILD collaboration to be proposed for the detector of the future International Linear Collider project. A prototype of 1m$^3$ has been conceived within the CALICE collaboration in order to validate this option. The prototype intends to be as close as possible to the one proposed in the ILD Letter Of Intent. Few units made of 1m$^2$ GRPC fully equipped with semi-digital readout electronics and new gas distribution design were produced and successfully tested. In 2010 we intend to produce 40 similar units to be inserted in a self-supporting mechanical structure. The prototype will then be exposed to TestBeams at CERN for final validation.

1. Introduction
As was explained in a previous paper [1], the use of high-granularity hadronic calorimeter is an essential ingredient for an efficient exploitation of the promising Particle Flow Algorithms technique [2]. Two kinds of such hadronic calorimeters were proposed in the ILD letter of Intent [3]. One of the two proposed options is based on using Glass Resistive Plate Chambers as the sensitive medium and stainless steel plates for absorber.

The use of gaseous detectors such as the GRPC ensures a good homogeneity of the sensitive medium. They should however, as for the scintillator-based option, satisfy strong constraints. In addition to be very efficient the GRPCs should be as thin as possible in order to reduce the construction cost of the whole detector. Indeed, the HCAL should be placed inside the magnetic field, reducing its thickness will hence reduce the radius of the magnet coil which is an important element of the detector cost. The GRPCs design should also provide negligible dead zones in order to keep the tracking capability as high as possible.

The high granularity is provided by the readout electronics system. The signal created by the passage of charged particles in GRPC detector is collected thanks to 1cm$^2$ pads etched on one side of the electronics board which is put in contact with the GRPCs. A pad is read out by one of the 64 channels of the HARDROC ASICs [4] fixed on the other side of the electronics board. The HARDROC ASICs are connected with each other through the electronics board using the DAISY chain scheme. This results in limited number of connections coming out of the sensitive medium. The ASIC provides 2-bit readout. The choice of this semi-digital scheme rather than the binary one was motivated by simulation studies which show that better performance can be obtained by the semi-digital scheme at high energy as shown in Fig. 1. This result can be explained by the fact that at high
energy many particles may go through one pad especially in the centre of the hadronic shower. Since
the extension of the avalanche created by charged particle in GRPC is of the order of few $\text{mm}^2$ [5] the
semi-digital readout with its three thresholds can help to distinguish among scenarios with few, many
and too many particles going through one pad. This improves on the energy measurement resolution
by estimating better the number of produced charged particles in the hadronic shower.

![Figure1: Energy resolution of hadronic shower created by pions with binary readout (black triangles)
and semi-digital readout (red squares).](image_url)

In order to reduce the power consumption the HARDROC is equipped with a power pulsing
scheme which reduces the consumption by a factor of 100 when applied in the envisaged ILC duty
cycle.

Results obtained with small GRPCs equipped with the semi-digital readout electronics system [6]
have allowed one to envisage building large GRPC chambers equipped with the same electronics.

In this paper we will describe the development realized to build $1\text{m}^2$ GRPCs satisfying the
requirements mentioned above as well as the associated electronics boards. The cassette to assemble
them and the mechanical structure to host the 40 envisaged ones will be detailed. The services and the
acquisition system of this prototype will be described. Finally the software and analyses preparation to
exploit the data of the future prototype are briefly mentioned.

2. Large GRPC development

The chambers to be used for the prototype are made of two glass plates of 0.7 mm and 1.1 mm
thickness. Precision ceramic balls of diameter 1.2 mm are used as spacers to separate the glass plates.
The number of balls (81) was fixed so that the deviation of the gap distance between the two plates
under the glass weight and the electric force when the high voltage is applied on the two electrodes
does not exceed 40 microns. The gas volume is closed by a glass fiber frame.

The resistive coating on the glass plates which is used to apply the high voltage and thus to create
the electric field in the gas volume was found to play important role in the pad multiplicity associated
to a mip [6]. To find the best coating for our chambers considerable efforts were made. Commercial
products like Licron® and Statguard® which are used for ESD applications were used and few large
chambers using those products were built and intensively tested. Both products failed to satisfy our
application either for long term stability under the high voltage (Licron®) or due to the impossibility
to obtain the surface uniformity needed for our application (Statguard®). Finally two products were
identified, both of which are based on colloids containing graphite and both can be applied using the
silk screen print method which ensures very uniform surface quality. One of these products is a single
component paint with a dry surface resistivity of $1\text{ to } 10\Omega/\square$. The second product comes as two
components which must be mixed by the user. The surface resistivity may be adjusted over a wide
range by changing the mix ratio. Both products require baking at around 170° C to attain a stable surface resistivity. The measured surface resistivity at various points over a 1 m$^2$ glass coated with the bi-component paint are shown in Fig. 2. The mean value is 1.2 MΩ and the ratio of the maximum to minimum values is 1.8. A study was also made of the repeatability of the surface resistivity between different mix batches. It was found that surface resistivity in the range 1-2 MΩ could be reliably reproduced, again with a factor of approximately two.

For large GRPCs the painting is applied on the whole glass plate except the zones situated 3 mm from the edges. This distance was optimized so the dead zone of the detector is reduced while external sparks due to the presence of absorber in the vicinity is completely eliminated.

![Figure 2: Surface resistivity for 1m$^2$ glass coated with bi-component colloidal graphite.](image)

Another important aspect of this development concerns the gas distribution within the GRPC. In order to improve on the gas distribution in large chambers taking into account the requirement that both gas outlets should be on the same side of the detector, new schemes were studied. The one we finally adopted allows us to improve the gas distribution by channelling the gas along one side of the chamber and releasing it into the main gas volume at regular intervals. A similar system is used to collect the gas at the other side of the chamber. A finite element model has been established to verify the gas distribution [7]. The simulation confirms that the gas speed is reasonably uniform over most of the chamber area and that this design significantly improves the distribution of gas with respect to a chamber with no gas channels.

### 3. Readout electronics board

As described in the introduction the signal produced by charged particles crossing GRPC can be collected thanks to 1 cm$^2$ pads on one side of the electronics board. The signal is then funnelled out to the ASICs fixed on the other side of the board. The board is made of 1.2 mm thick, 8-layer Printed Circuit Board (PCB) which was designed to reduce the noise as well as the cross-talk among the different channels. This kind of PCB is currently limited in size so the 1m$^2$ area needed to read out the 1m$^2$ GRPC is realized using six PCBs of area 50 x 33.3 cm$^2$. The PCBs are linked together using special low-profile flexible connectors. Each of the six PCBs supports 24 ASICs, The PCBs are regrouped by two and connected to a small board called Detector InteFace board (DIF). The DIF which hosts FPGA device controls the transmission of configuration parameters to the 48 ASICs and
the reception of data collected from them. The DIFs are connected to the electronics board through flexible Kapton® connectors.

4. Cassette description
The GRPC and its associated electronics are housed in a special cassette which protects the chamber and ensures that the readout board is in intimate contact with the anode glass (see Fig. 3). The cassette is a thin box consisting of 2 mm and 3 mm thick stainless steel plates separated by 6 mm wide stainless steel spacers which form the walls of the box. These spacers are precision machined so no space left between the two cassette plates and the sensitive medium. The dimensions of the plates are such that a space of 2 mm wide is left between the GRPC and the spacers. This space is filled with insulating product to protect against sparks. One of the two plates is 20 cm larger than the other. This allows one to fix the three DIFs as well as the gas outlets and the high voltage box.

The electronics board is assembled thanks to a polycarbonate spacer (‘PCB support’ in Fig. 3) which is also used to fill the gaps between the readout chips and to improve the overall rigidity of the detector. The board is then fixed on the small plate thanks to tiny screws and the new set is fixed on the other plate which hosts the detector and the spacers. The whole width of the cassette is 11 mm with only 6 of them corresponding to the sensitive medium including the GRPC detector and the readout electronics. The remaining 5 mm are those of the stainless steel plates and constitute a part of the HCAL absorber.

One fully equipped cassette was produced and tested in TestBeam at CERN recently. Efficiencies of 96±2 % were measured in many different zones of the 1m² including those where the electronics boards are connected. This validates the cassette concept which ensures the homogeneity of the whole sensitive medium made of the detector and the readout electronics. Other cassettes are being built and tested. These obtained results allowed us to envisage the construction of the 40 units needed for the prototype.

5. Mechanical structure
The prototype will be made of 40 of the previous cassettes separated by 39 stainless steel plates of thickness 1.5 cm each. With the 5 mm of each of the 40 cassettes, the total weight will exceed 6 tones. A self-supporting mechanical structure was conceived in which the absorber plates are part of the structure itself. This leads to a very robust structure. To achieve this, precision spacers of 13 x 18 mm² sections each will be used to fix two consecutive plates on three of the their four edges thanks to well distributed bolts. The extra 2 mm with respect to the cassette width accounts largely for the fabrication tolerance of the plates and the cassettes. This was shown from real insertion tests of the cassette in a mechanical structure made of two plates. The tests showed also that the insertion of the cassette from above is the most suitable way.

The advantage of this structure in addition to its robustness is its flexibility. Additional units can be added in the future if one wishes to increase the equivalent number of the interaction lengths.
Cassettes made of different detection technologies (MICROMEGAS, GEM…) can also be used in this structure.

6. Prototype thermal modelling

The technological prototype will feature a high number of electronics channels, the heat from which must be evacuated. Power pulsing of the electronics will in principle ensure that the power per channel is extremely low (<10 μW); nevertheless a thermal model has been developed to study the worst case scenario of no power pulsing. In this scenario, the power consumption is a factor 100 higher. Two detector planes with electronics and three absorber layers were modelled. Based on symmetry arguments, it was considered sufficient to simulate only one quarter of the full area of each layer. Cooling was assumed to be entirely passive, i.e. by convection only, for an ambient temperature of 20° C. Under these conditions, the model predicts a maximum rise in temperature of 5° C. Active cooling is therefore considered unnecessary in the present design.

7. Prototype services

The high voltage system will be based on the Cockcroft-Walton voltage multiplier. Such a system allows low voltage (0-5 V) cables to be used up to the cassettes, greatly reducing the volume of cable insulation inside the detector. This constitutes an important improvement for the cabling issues in the future ILC detector. A suitable module is being developed in collaboration with Iseg Company. The module, one for each RPC, will deliver up to 10 μA with a voltage range of 0-10 kV. In addition, it must be sufficiently low-profile (< 24 mm) to fit between cassettes. Control and monitoring of voltages will be available via Ethernet link.

A gas mixture based on tetrafluoroethane (C2H2F4) will be used, with SF6 and isobutane quenchers. A 40-channel gas distribution system has been ordered. Precision mass flow meters are used to regulate the flow of each gas component to within ±2%. The gases are mixed and then split off into 40 parallel outlets. The flow from each outlet can be independently regulated and monitored using rotameters. Each of the 40 return lines is equipped with a bubbler. The system is certified for use in flammable environments to ATEX zone 2 level.

8. Prototype acquisition system

A central acquisition system based on a common scheme adopted by the CALICE collaboration for the different technological prototypes is under construction for the Semi-Digital hadronic one. The acquisition system is based on an Off-Detector Receiver (ODR) which is a PC interface. The ODR communicates with few Link/Data Aggregator boards (LDA). Those boards play a central role. They allow to transmit the configuration parameters to the appropriate DIFs and to transmit the collected data from the previous to the ODR after sorting them out. In order to reduce the needed number of LDA a Data Concentrator Card was developed in the case of the SDHCAL. Each DCC receives the data from 9 DIFs (corresponding to 3 cassettes) and compresses them before transmitting them to the LDA. Using 14 of the DCC limits the needed number of LDA boards to two for the entire SDHCAL prototype. In order to synchronise the 120 DIFs a Clock and Control Card (CCC) was also developed. It provides a common clock to the different DIFs through the LDA-DCC. It allows also trigger distribution as well as Busy signal handling. Tests are ongoing in order to validate the whole system.

9. Software preparation

A GEANT4-based simulation of the SDHCAL prototype was elaborated. Realistic description of the sensitive medium taking into account the details of the different materials and the dead zones was adopted. To describe the GRPCs response adequately a sophisticated treatment using the avalanche description based on Polya function approach was used and its parameters deduced from a dedicated
study of GRPCs realized with analogue readout electronics. In addition the pads multiplicity was correctly introduced in the simulation through a model using the distance between the incoming particle impact and the edge of the associated pad. The model parameters were fixed in order to reproduce pad multiplicity obtained from TestBeam data. This realistic description will enable us to perform efficiently comparisons between the observed data and the different hadronic shower models used in the simulation in the future.

10. Analyses preparation

In order to be able to exploit the data delivered by the future SDHCAL prototype, many analyses are ongoing. They are trying to get use of the high granularity of the SDHCAL as well as the 2-bit readout system. Methods based on Neural Network are being developed in order to improve on the energy resolution of the hadronic shower energy. They provide important information which allows us to fix the values of the three thresholds associated to the semi-digital readout. Tracking methods using the Hough Transform to extract mips from the hadronic shower so they can be used for alignment and online control of the detector are being elaborated. Minimum Spanning Tree algorithms are also being investigated in order to separate efficiently the contribution of two particles inside the SDHCAL prototype before to measure their energy separately. This will constitute an important element to test the PFA algorithms

11. Conclusion

An important progress has been achieved toward the construction of a Semi-Digital Hadronic Calorimeter. First cassettes satisfying the requirement of efficiency, hermeticity and thickness were built and successfully tested. Services of the future prototype are under construction. A self-supporting mechanical structure is conceived and being built. Acquisition system capable of dealing with 368640 channels is well advanced and tests to validate it are ongoing. In addition, software and analyses activities are followed actively in order to be ready to exploit data from the prototype whose completion is expected by the end of 2010.

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